

# Advances in Surf. Treatments

Vol II

86043

## RESIDUAL STRESSES AND FATIGUE OF SURFACE TREATED WELDED SPECIMENS

D. G. Bellow, M. Wahab and  
M. G. Faulkner

*Department of Mechanical Engineering, University of Alberta, Canada*

### ABSTRACT

An experimental program was undertaken to evaluate the effect of induced compressive stresses due to various peening and thermal treatments on the fatigue life of a butt welded medium strength steel (Cb-50). Residual stresses were measured using x-ray diffraction and the results were compared with hardness values taken at the surface and through the thickness of the specimens. It was found that of all post weld treatments studied the stress peened specimens gave the most improvement in fatigue strength over that of the as-welded condition and approached 82% of the fatigue strength of the base metal at a fatigue life of  $2 \times 10^6$  cycles. On the other hand annealing only showed an improvement of 14% over that of the as-welded condition.

It was found that a good linear correlation existed between the induced residual stresses at the toe of the weld and the fatigue strength evaluated at  $2 \times 10^6$  cycles. However, for residual stresses of less than 130 MPa very little improvement in fatigue strength was evident.

Surface residual stresses were compared with Almen strip readings and the depth of work hardening. It was found that the Almen strip readings did not give as consistent an indication of work hardening as did measurement of the residual stresses.

### KEYWORDS

Butt-welds, stress peening, shot peening, single and multiple point hammer peening, annealing, fatigue strength, residual stresses.

### INTRODUCTION

The development of residual stresses in welded constructions is intrinsic to the welding process. These residual stresses often cannot be entirely removed by post-heating. While some investigators (Munse, 1964) have contended that residual stresses do not have any significant influence on fatigue life, others such as Dugdale (1959) have demonstrated a substantial effect in the case of small notched specimens. Furthermore, it has been known for some time (Buhler and Buchholtz, 1933; Horger and Neifert, 1945) that residual stresses are redistributed during the course of cyclic tension.

Residual stresses are caused by local yielding in an otherwise elastic body and for most welded structures they are confined to the neighbourhood of the welds. A model for following the development of residual stresses has been suggested by Parlane (1981). This model explains that the magnitude of the residual stresses is a function of the temperature difference between base material and the weld butt and can vary, depending on the conditions, up to the yield stress.

The investigation of the effect of residual stresses requires the study of the influence on the endurance and/or fatigue limit and the influence of the cyclic stresses on the redistribution of the residual stresses. Parker (1957), Tall (1964), Munse (1964), Gurney and Maddox (1973), Harrison (1981) among others have observed that the fatigue strength of stress relieved butt welded joints was improved over those in the as-welded condition. In particular, Harrison (1981) showed that when the applied stress range was purely tensile the residual stress had little effect but that if the stress cycle passed through zero the compressive components appeared to be more damaging.

The welding process is a complex one and depends on many variables. Thus, to investigate the influence of residual stresses on the fatigue life of welded joints the experiments must be done under closely controlled conditions. Most of the studies on the fatigue life of welded joints reported in the literature have shown that appropriate mechanical and/or thermal treatments have improved the fatigue life but the manner in which the residual stresses interact with the applied cyclic stress and the changes that occur during cycling is less known. The object of this paper is to show how the cyclic loading in the fatigue cycle affects the distribution of residual stresses in butt welded joints. In a subsequent paper a mathematical model will be developed for prediction of the crack initiation and propagation phases taking into account the residual stress behaviour noted here.

## EXPERIMENTAL

The experiments were designed to obtain the base material properties for the prediction of total fatigue life and to determine the experimental data (S-N curve) for mechanically and thermally treated welded joints. High cycle pulsating tension tests were performed and the magnitude of the residual stresses and the effect of these on the fatigue life was observed. Fatigue testing was conducted on an MTS closed-loop servo-controlled hydraulic test system.

### Fatigue Specimens

The high cycle fatigue specimens were made by welding two 127 mm wide by 6.35 mm thick plates out of as-rolled Columbium-50 steel (0.02% C, 1.2% Mn, 0.04% P, 0.05% S and 0.005% Cb). This steel was selected for its weldability and relatively high yield strength. The plate edges were machined straight and bevelled at 45° to a depth of about 1.6 mm. An automatic submerged arc welding process was used for a double-vee butt weld. The welding electrode was an Oxweld #36 (0.14% C, 2.0% Mn, 0.017% P, 0.024% S and 0.05% Si). The welds were all fluoroscoped, and some ultrasonically, to check for flaws and then sawn into 76 mm wide strips with the weld axis transverse to the saw cut. The longitudinal edges of the welded specimens were machined parallel using a milling cutter.

### Surface Treatments

The surfaces of the welds as well as the adjacent base metal were subjected to the following mechanical surface treatments:

- (1) single point hammer (6.4 mm diameter)
- (2) multiple point hammer (19 needles of 3.2 mm diameter each)
- (3) glass shot beads (0.2-0.3 mm diameter)
- (4) steel shot (0.6-1.2 mm diameter)

The exposure time for the single and multiple hammer peening was between 25 and 35 s per  $650 \text{ mm}^{-2}$  of surface area covered. The duration of exposure for the glass and steel shot was six and eight minutes respectively. Visual checks were made to ensure the weld toe and adjacent base metal was evenly covered. To assist in this a dye penetrant along with an ultraviolet light was used. Full coverage of the surface during peening removed the coating so that incomplete coverage was detected by the ultraviolet light. In addition to using standard size Almen strips the depth of peening was measured by sectioning near the toe of the weld a plane inclined approximately  $10^\circ$  to the peened surface and measuring hardness using a Knoop indenter and 300 g load (Faulkner and Bellow, 1972).

A fifth technique for inducing compressive residual stresses was achieved by tensile preloading. The welded specimens were preloaded to approximately 90% of the yield of the base metal. Electrical resistance strain gauges were applied to the base metal adjacent to the weld to ensure that the base metal remained elastic. The rate of preloading was  $7.5 \text{ kN min}^{-1}$ . Stress measurements were made using an x-ray diffraction technique.

Another surface treatment evaluated was stress peening where the specimens were preloaded first to 90% of the yield of the base metal and then peened. A variation of this was also tried by first peening and then preloading. In both these cases the stresses were measured before and after the treatment.

To study the effect of annealing on the fatigue life some specimens were annealed at  $550^\circ\text{C}$  for 30 min. and slowly cooled (5 to 6 hrs).

### Fatigue Testing

Specimens were mounted in the fatigue machine and a uniaxial cyclic tension load was applied. The dynamic peak load was controlled and the test was stopped automatically, due to a change in strain response, when a small fatigue crack occurred. The initiated crack was checked with dye penetrant and ultraviolet light. The test was then started again to obtain the propagation life of the specimen until complete fracture occurred.

### Measurement of Residual Stresses

All stress measurements were performed using the Thomas-B double exposure x-ray diffraction technique (Sproull, 1946; Cullity, 1978). The x-ray method was calibrated with strain gauges and other techniques yielding good correlations between the various methods as shown in Fig. 1. Before each specimen was tested in fatigue the residual stresses were measured at the toe of the weld. Additional stress measurements were made for selected specimens at various stages in the fatigue life and at the end of fatigue cycling. Residual stresses were also measured across the thickness of the base metal and across the thickness of the butt welded specimens to examine the presence of any stress gradient. To compensate for the selective action of the x-rays at least three exposures to each setting were taken.

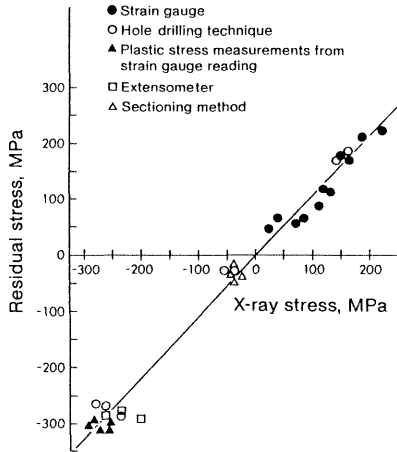


Fig. 1. Calibration of x-ray stress measurements with other techniques.

### Hardness Tests

Hardness tests were carried out on peened and unpeened welded specimens. The peening intensity, as measured by surface hardness, and the depth of work hardening were measured with a Knoop indenter. Micro-hardness readings were obtained at the weld toe, untempered weld metal and the tempered weld metal zones for the untreated specimens using a Vicker's indenter and a 300 g load.

## RESULTS

### Distribution of Welding Residual Stresses

The distribution of residual stresses was measured across the welding joint. Since most fatigue cracks originated on the "second pass" side of the weld this was the side on which most stress measurements were made. Typical residual stress patterns for three specimens are shown in Fig. 2.

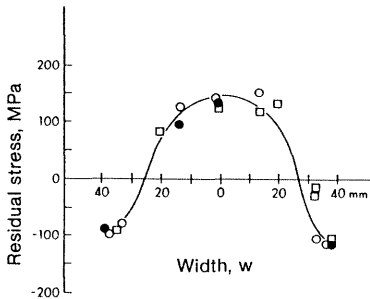


Fig. 2. Residual stress distribution near the toe of the weld.

From this figure it is clear that the residual stresses are maximum tensile (140-170 MPa) across the weld and decrease to compressive stresses between 100-120 MPa 30 mm away from the center of the weld.

In another test three untreated specimens were cycled at different stress levels 0-145 MPa for  $0.5 \times 10^5$  cycles, 0-165 MPa for  $10^3$  cycles, and 0-265 MPa for  $10^5$  cycles and the test terminated before fatigue cracks initiated to evaluate the effect of cycling on the redistribution of the original residual stress pattern observed in Fig. 2. These results are shown in Fig. 3. Although the number of cycles and dynamic loads were different in each case the results show that the residual stress pattern changed, depending on dynamic load, during fatigue cycling and that for the 165 MPa dynamic load the pattern had changed at  $10^3$  cycles.

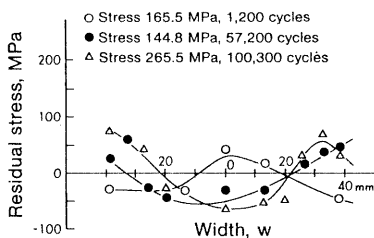


Fig. 3. Distribution of residual stresses after fatigue cycling.

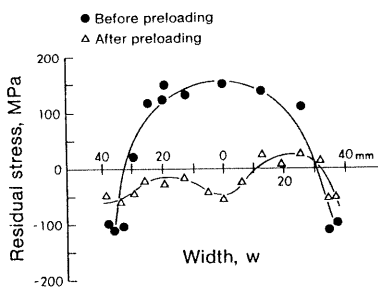


Fig. 4. Change in residual stress pattern after preloading.

Measurement of residual stresses through the thickness of the weld were made where it was found that the compressive stresses existed to a depth of about 0.08 mm whereas on the surface of the base metal compressive stresses between 21-35 MPa were measured.

#### Compressive Stresses of Surface Treated Welds

To evaluate the effect of tensile preloading residual stresses were measured near the toe of the weld before and after preloading. A typical result is shown in Fig. 4 where an initial tensile residual stress of 150 MPa changed to a compressive stress of about 50 MPa after preloading. Other tests showed the same result except that there was less uniformity in stress distribution observed after than before preloading.

Residual stresses were also measured on specimens before and after mechanical surface treatment. Figure 5 shows the manner in which the tensile residual stresses across the weld were modified to almost uniformly compressive stresses after peening. The single and multiple point hammer peening yielded residual compressive stresses of 150 MPa and 170 MPa respectively whereas the glass and steel shot compressive residual stresses were measured at 60 MPa and 110 MPa respectively. For comparison the residual stresses for an annealed specimen were near zero. The results of stress peening showed a compressive residual stress of 170 MPa and no difference was noted whether the specimen was peened and then preloaded or preloaded and then peened.

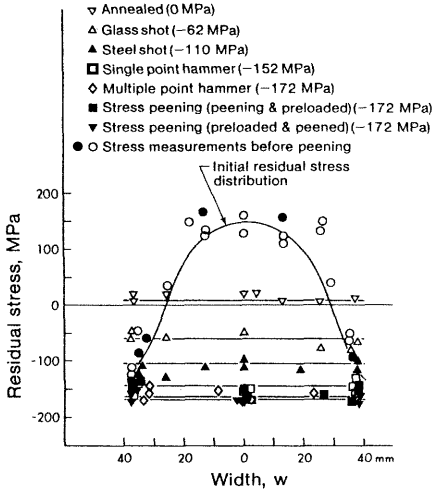


Fig. 5. Compressive stresses by various methods.

### Fatigue Results

A summary of fatigue results is shown in Fig. 6. Each curve was drawn through the mean of at least four tests at each test load and for each curve the test was run at four and sometimes five different stress levels. From these results it is seen that at a life of  $2 \times 10^6$  cycles the fatigue strength of the as-welded condition was 145 MPa or 43% of the base metal which was at 340 MPa. Table 1 summarizes the fatigue strengths at  $2 \times 10^6$  cycles in order of improvement from the as-welded condition to the base metal

From Fig. 6 and Table 1 it is evident that stress peening improved the fatigue strength from the as-welded condition more than any other treatment studied. From the residual stress patterns in Fig. 5 it was shown that there was little distinction in stress peening whether the specimen was peened before or after tensile preloading. This same result was noted in the fatigue results and thus in Fig. 6 and Table 1 both results were combined and noted as "stress peened". The next best surface treatments were achieved with the multiple point and single point hammer peening and steel shot. Each of these showed about the same improvement 70-79% over the as-welded condition. As might be expected the benefits of glass shot, while measurable at 40% better than the as-welded condition, were not as pronounced as for the heavier peened surfaces. Finally, annealing and preloading produced only small improvements of 14-17% over the as-welded condition.

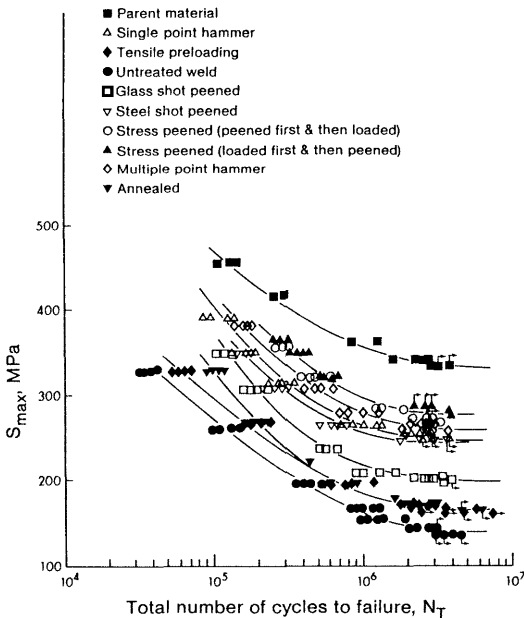


Fig. 6 Comparison of fatigue tests.

TABLE 1 Fatigue Strengths at  $2 \times 10^6$  Cycles

Treatment	MPa @ $2 \times 10^6$ cycles	% Improvement over as-welded	% of base metal
Base metal	340	134	100
Stressed peened	280	93	82
Multiple point	260	79	76
Single point	250	72	74
Steel shot	245	70	72
Glass shot	200	40	59
Tensile preload	170	17	50
Annealed	165	14	49
As-welded	145	0	43

From the data plotted in Fig. 6 an induced stress value was calculated as the absolute value of the difference between the initial residual stress at the toe of the weld (150 MPa) and the induced compressive stress due to various forms of post welding treatment. The fatigue strength was evaluated at  $2 \times 10^6$  cycles. The induced stress was plotted against the improvement in fatigue strength over the as-welded condition and shown in Fig. 7. A fourth order polynomial curve was fitted through the data and the equation is shown in Fig. 7. In addition, two straight lines were drawn through the data, one was drawn as a "best fit" straight line through the measured data but not including the origin, the other was drawn assuming the origin was a valid experimental point. For the two straight lines, with and without taking the origin as a

data point, the correlation co-efficients were 0.91 and 0.96 respectively. As might be expected the results show that as the induced compressive stress due to post welding treatment increases so does the fatigue strength.

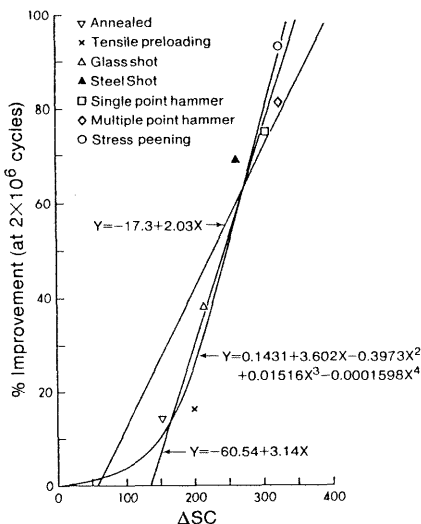


Fig. 7. Improvement in fatigue strength as a function of induced stress.

If the linear correlation of the data (without including the origin) is accepted as valid then for induced stresses of less than 130 MPa there is no improvement in fatigue strength over the as-welded condition.

#### Depth of Work Hardening

It is interesting to note the depth of work hardening as a consequence of the various post-treatments studied. The data showing the Knoop hardness (300 g load) versus the depth from the surface are plotted in Fig. 8. The glass shot produced a depth of work hardening of 0.2 mm, for steel shot the depth was 0.43 mm, for multiple and single point peening the depth was 0.69 mm and 0.76 mm respectively and for both forms of stress peening the depth of work hardening was 0.7 mm.

A consistent trend was found between the residual stress levels and the depth of work hardening. Although the depth of work hardening was slightly more (0.76 vs 0.69 mm) for single point than for multiple point hammer peening the improvement in fatigue strength by multiple point hammer peening was greater. This was probably the result of insufficient peening applied at the weld toe due to the large radius of the peening hammer. However, the compressive residual stress level was higher for multiple point hammer peening than for single point hammer peening.

As it is quite common to measure peening intensity by means of Almen strip tests a comparison between Almen strip readings and depth of work hardening is shown in Fig. 9. Also shown in Fig. 9 is the induced compressive residual stress versus the depth of work hardening. These two plots show that the depth of work hardening correlates better with residual stress than with the Almen strip values. Evident from Fig. 9 is the fact that the depth of work hardening

approached a constant value of 0.9 mm at an induced compressive stress of 170 MPa.

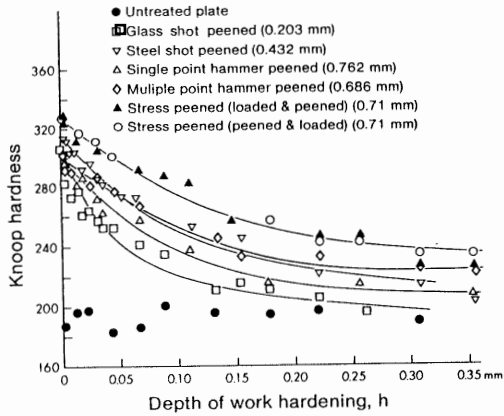


Fig. 8. Hardness versus depth of work hardening.

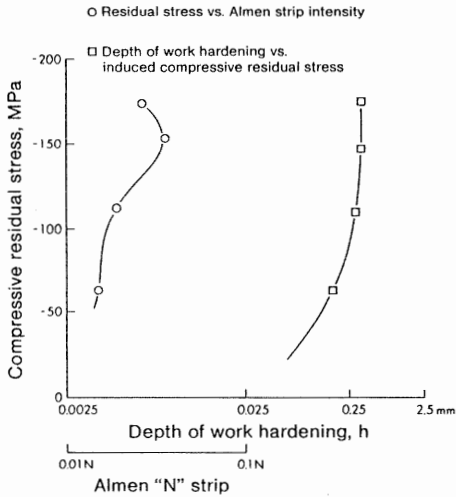


Fig. 9. Depth of work hardening and Almen strip intensity versus induced residual stress.

#### CONCLUSIONS

A series of experiments were conducted to evaluate the influence of residual stresses on the fatigue life of a butt-welded medium strength steel. A variety of post weld mechanical and thermal treatments were evaluated and it was found by stress relieving and inducing compressive residual stresses the improvement

in fatigue strength at a life of  $2 \times 10^6$  cycles could be as much as 93% over the as-welded condition. Of the post weld treatments evaluated stress peening provided the most improvement whereas annealing provided the least at only 14% over the as-welded condition.

The depth of work hardening due to peening increased exponentially and approached a constant depth of 0.9 mm as the surface residual stress of 170 MPa was attained.

Finally, it was found that there was a good linear correlation between the induced compressive stress due to post weld surface treatment and the fatigue strength evaluated at  $2 \times 10^6$  cycles. For residual stresses less than 130 MPa no beneficial effect in fatigue life is to be expected.

#### ACKNOWLEDGMENTS

The authors wish to thank the sponsors of this experimental program, Natural Sciences and Engineering Research Council (Canada), for the financial assistance received under grants A-2705 and A-7514. Thanks are also due to Messrs. T Villett, J Foy, A Muir, B Cielin and M Schubert of the Mechanical Engineering Department for their assistance in the experimental programs.

#### REFERENCES

- Buhler, H., and H. Bucholtz (1933). The effect of residual stresses on the dynamic bending strength, Mitt. Forsch. Inst., 3 (8), 235-248.
- Cullity, B. D. (1978). Elements of X-ray Diffraction. Addison-Wesley.
- Dugdale, D. S. (1959). Effect of residual stresses on fatigue strength. Weld Res. Suppl., 45-48.
- Faulkner, M. G., and D. G. Bellow (1972). Improving the fatigue of life of butt-welded medium strength steels. Proc Appl. of Solid Mech. Univ. of Waterloo.
- Gurney, T. R. and S. J. Maddox (1973). A reanalysis of fatigue data for welded joints in steel. Weld. Res. Int., 3(4), 1-54.
- Harrison, J. D. (1981). The effect of residual stresses on fatigue behaviour. Weld. Inst. Mono., 9-16.
- Horger, O. J., and H. R. Neifert (1945). Shot peening to improve fatigue resistance. Soc. Exp. Stress Anal., 1-10.
- Munse, W. H. (1964). Fatigue of Welded Steel Structures. Welding Research Council, New York.
- Parker, E. R. (1957). Stress relieving of weldments. Weld. Res. Suppl. 433-440.
- Parlane, A. J. A. (1981). Origin and nature of residual stresses in welded joints. Res. Stresses and Their Effect. Welding Institute, pp. 1-4
- Sproull, W. T. (1946). X-Rays in Practice. McGraw-Hill.
- Tall, L. (1964). Residual stresses in welded plates - a theoretical study, Weld. Res. Suppl. 10-23.