A Concept for Preventing Repeated Weld Repairs of Bridge Structures

W.H. Welsch
Manager of Metallurgy, Metal Improvement Company, Inc., Carlstadt, New Jersey

ABSTRACT: Recent studies and publications have discussed methods of improving fatigue life in welded structures. The writer investigates the mechanism for fatigue failures in weldments as well as the data supporting various post weld failures. The paper will deal in depth with the control of these processes and how to achieve consistent improvements in post weld treatments.

KEY WORDS: shot peening, fatigue, fatigue strength, post weld stress relief

INTRODUCTION

In a recent study, all but 5 of the 130 cases of cracking in bridge structural members were attributed to fatigue (1). The majority of these fatigue cracks initiated adjacent to a weld (Fig. 1). This is not surprising, since welds introduce three conditions which reduce the fatigue strength of the welded joints.

First, the weld bead creates a surface discontinuity or stress riser. This stress riser can double the calculated maximum surface stress from the applied load and thereby lower the fatigue strength.

Second, as the last pass of weld metal cools and contracts, high tensile stresses remain in the weld and adjacent heat affected zone (Fig. 2). In the past these detrimental tensile stresses were written off as being harmless. Since the residual tensile stresses are high, approaching the yield strength of the steel, they were expected to be reduced by yielding at the first application of a load during normal service. This is true - a reduction in residual surface stresses does occur. Unfortunately, since the loads are low by prudent design, the reduction of residual surface tensile stresses is minimal.

Third, improper welding can introduce porosity, slag inclusions and poor fusion. When the weld is inspected using nondestructive means, these discontinuities are normally revealed and corrective action initiated. In some steels welding can also introduce a harder, embrittled area not detected by nondestructive testing. This harder area in the heat affected zone will increase the notch sensitivity. The result is cracking during sub-zero winter weather which can provide an avenue for fatigue crack propagation.

With all these contributing factors available to initiate fatigue cracks, praise is in order for the designers, welders, inspectors and consultants who have kept fatigue cracking to a minimum. What follows is a list of the various methods used in the past and also a new method proposed to prevent cracking in the future.

METHODS TO PREVENT FATIGUE CRACKING

The assumption was that fatigue cracking would never occur since bridges were over designed, the steel was selected for its superior fatigue properties, and residual tensile stresses would relieve themselves from the vibrations set up by traffic. Unfortunately, in many instances the formation of a fatigue crack provided a surprising form of post weld stress relief. Once fatigue cracks did appear, the reasons for the cracks were explained by poor design or overload. Overloading was corrected by restricting the traffic to automobiles and exempting trucks. Most engineers in the bridge community were comforted by the fact they did not use the particular design that failed. The few that had fatigue critical details used the following methods of repair:

Method #1

The cracks appearing in the box girder design for instance, (Fig. 3) were arrested by drilling holes at the end of the crack or at the crack initiation point as a preventative. This is considered a temporary solution and there is no way of predicting when the cracks will reappear in the drilled holes. Variables such as the residual surface stresses in the hole and how the drill was extracted from the hole cannot be controlled. Fast cutting or drilling of the hole can create high temperatures that will leave high residual tensile stresses. When the drill is removed from the hole, a detrimental stress riser may be left by a scratch parallel to the hole axis.

Method #2

Weld repair, the more economical solution when compared to splicing, was not adopted in many cases since the fatigue crack was expected to reappear within the same time frame or sooner. Large fatigue cracks as shown in Figure 1 have mostly been spliced by bolting.

Method #3

A method studied and implemented on new construction and particularly on cover plate termination welds is grinding (3). Bridges presently being erected exhibit a blending of the cover plate end and lower I-beam flange with a weld so streamlined its configuration suggests it would have to meet an aerodynamic test. A lot of grinding is required for such a blended weld, and it is a shame little thought was given to the second fatigue strength lowering characteristic listed above - namely, residual tensile stresses. The heat generated from severe grinding may leave the surface in tension with magnitudes of tensile stresses equal to those of welding. And if the grinding is not monitored properly, severe grinding heat checks will actually provide fatigue crack initiation sites and lower the fatigue strength even more. Studies have shown the magnitude of surface stresses are inversely proportional to the fatigue strength (Fig. 4) with all other variables being equal. In other words, the higher the surface stresses (residual stress plus applied stress), the lower the fatigue strength.

The use of heat to stress relieve such an I-beam after welding and grinding has been considered and then abandoned. The potential distortion that would develop during heat stress relieving was one concern. The reduction of the tensile strength from high stress relieving temperatures was the other concern because of the annealing effect.

The American Welding Society Welding Handbook not only advises the elimination of tensile stresses from welding on fatigue critical components but also suggests:

> "...it may be advantageous to induce compressive residual stress in critical areas of a weldment where cyclic applied tensile stresses are expected. This may be accomplished by a welding sequence that controls residual stress-

es from welding, or by a localized treatment that acts to place the surface in compression" (6).

Method #4

Research initiated by AASHTO's National Cooperative Highway Research Program in the 1970's, reported that a technique known as peening inhibited the cracking process (4). By impacting the area of the weld toe with a pneumatic hammer, fatigue cracks were prevented from returning on a 28 span steel bridge on Interstate 95 in Connecticut. The initial cracking of the cover plate termination welds occurred after 13 years of exposure to high volume traffic. The peening retrofit performed in 1978 on 700 cover plate ends saved more than one million dollars compared to bolted splices and is still crack free in 1989.

When the New Jersey Department of Transportation (N.J.D.O.T.) wanted to have cover plate welds peened on a bridge over Route 46 in 1983, their contractor was unable to find anyone willing to perform the pneumatic hammer peening process. It is a difficult, if not impossible, task to hold a 10 pound hammer over your head and apply a constant pressure on the hammer to pound a 3.17mm (1/8") wide groove in the weld toe. Continuous performance of this rigorous work may also result in an affliction affecting the nervous system in the operator's hand known as Carpal Tunnel Syndrome. The N.J.D.O.T. adopted a controlled shot peening specification and the work on the Passaic

Avenue Bridge was completed in three days by the local Metal Improvement Company, Inc. division located in Carlstadt, New Jersey (Fig. 5). The same specification meeting MIL-S-13165 controls has been presented to AASHTO for adoption and it is hoped that the Transportation Research Board will recommend further study to determine how many stress categories will be raised by the controlled shot peening process (7).

CONTROLS

The deficiency common to all the previously tried methods to prevent fatigue cracks in weldments is a lack of control. Hand held grinding, hand held drilling, or hand held peening tools introduce a variable that was eliminated with MIL-S-13165C specification shot peening equipment (Fig. 6).

"3.2 Equipment

3.2.1 Automatic Shot Peening

The machine used for shot peening shall provide means for propelling shot by air pressure or centrifugal force against the work, and mechanical means for moving the work through the shot stream or moving the shot stream through the work in either translation or rotation, or both as required. The machine shall be capable of reproducing consistently the shot peening intensities required....The equipment shall

> continuously remove broken or defective shot so that this shot will not be used for peening" (8).

This separator provides continuous removal on non-round shot that is produced when the steel shot fractures.

The intensity is measured at fatigue critical locations with the use of Almen strips. The area is checked for coverage or complete cold work by coating the weld and heat affected zone with a fluorescent dye. The dye breaks up as the shot impact stretches the surface to form the dimple, thereby giving the quality control inspector the leverage to insist on longer peening times if needed.

The fluorescent dye has another function beyond checking for coverage. The dye works its way into porosity, inclusions, or cracks opened up by the peening and, therefore, provides an additional quality control on the weld by revealing shallow, subsurface flaws.

A third quality control feature offered by controlled shot peening is the fact that a harder, embrittled heat affected zone will be visually obvious after peening. There will be shallower dimpling in the harder areas.

SUMMARY

Engineers and designers have learned to appreciate the economy of welding and need to address methods of improving fatigue strength. Shot peening per MIL-S-13165C, offers the most promise by dealing with the three conditions of fabrication which reduce fatigue strength.

1. The multiple impacts of round, uniform steel shot propelled in automatic equipment negate the affects of the stress riser at the toe of the weld.

2. Cold working of the weld and heat affected zone to a specified depth induces residual compressive stresses of -42,000 psi on a 70,000 psi ultimate tensile strength steel such as ASTM A588. Tensile stresses from welding or grinding can peak at 42,000 psi at the metal surface which amounts to a 82,000 psi overall stress reduction.

3. The fluorescent tracer, applied prior to shot peening to check for overlapping impacts, is able to expose cracks, weld porosity, and inclusions not visible prior to peening. The retention of the fluorescent dye in crevices at the toe of the weld, and in porosity and inclusions opened up by peening gives the quality control inspector a chance to reject poor grinding or weld quality. A variation in dimple diameter may also expose embrittled areas in the heat affected zone.

Since fatigue strength is inversely proportional to residual surface stresses and shot peening provides the greatest surface stress reduction, controlled shot peening offers the most effective post weld stress relief method to solve the problem of fatigue in steel bridge component details.

BIBLIOGRAPHY

(1) "Welded Repair of Cracks in Steel Bridge Members", E. N. Gregory, G. Slater and C. C. Woodley.

(2) SAE Design Handbook

(3) "Specification for Weld Toe Grinding and Peening to Improve Fatigue Strength", G. S. Booth.

(4) "Detection and Repair of Fatigue Damage in Welded Hyway Bridges", John W. Fisher, Hans Hausammann, Michael D. Sullivan, Alan W. Pense.

(5) "Surface Integrity of Machined Components - Residual Stress and Fatigue", K. Neailey.

(6) Welding Handbook, Eighth Edition, American Welding Society

(7) "Bridge Fatigue Guide", Dr. John W. Fisher, American Institute of Steel Construction 1977

(8) "Shot Peening of Metal Parts" MIL-S-13165C.

Suggested Additional Reading:

"Evaluating the Effects of Residual Stresses on Notch Fatigue Resistance", Harold S. Reemsnyder.

"Fatigue Properties of Welded Roller-Quenched and Tempered (RQ) Steels", Harold S. Reemsnyder.

"Preliminary Investigation of the Effect of Controlled Shot Peening on the Fatigue Strength of Fillet Welded Joints", S. J. Maddox and J. C. Summers.

APPENDIX A

PROPOSED SPECIFICATION

FOR

CONTROLLED SHOT PEENING

OF

FATIGUE CONTROL STEEL BRIDGE COMPONENT DETAILS

SUBMITTED TO AMERICAN ASSOCIATION OF

STATE AND HIGHWAY TRANSPORTATION OFFICIALS

JULY 1988

SPECIFICATIONS FOR CONTROLLED SHOT PEENING OF STEEL BRIDGE FATIGUE CRITICAL COMPONENT DETAILS

I REASON FOR SHOT PEENING

The purpose for shot peening is to increase the fatigue life by inducing a layer of compressive stresses below the surface. This compressed stress layer introduced by cold working the surface will:

1 - Eliminate high tensile stresses from welding, grinding, machining and straightening.

2 - Obliterate stress concentrations at the toe of the weld, heat checks from abusive grinding and machining and grinding marks.

3 - Serve as a quality control tool by exposing subsurface porosity, cracks or inclusions.

II REFERENCES

MIL-S-13165 This specification may be obtained by telephoning 215/697-3321 or writing to Defense Industrial Supply Center, 700 Robbins Avenue, Philadelphia, Pa. 19111.

III The depth of compressive stresses should adhere to the following guidelines:

1 - Maximum depth of compressive stresses should be

limited to 5% of the thickness of the component.

2 - Minimum Almen intensities should be such that the peening obliterates any surface discontinuities. Failure to obliterate grinding marks, etc. is an indication a higher intensity may be required.

3 - Failure to remove the Dyescan tracer liquid (see sample shot peening specification, this specification and paragraph 6.11(b), page 11, of MIL-S-13165C) in cracks or crevices may require higher intensity or grinding prior to peening to remove the subsurface flaw.

4 - A corrosion allowance may be added to minimum peening intensities indicated in Table VI, page 16, of MIL-S-13165C.

5 - The peening of members with known fatigue cracks is not advisable. Elimination of cracks by grinding and building up to by welding and then peening is the suggested practice. If peening is used as a temporary fix, dye penetrant nondestructive testing is suggested after peening to insure the depth of compressive stresses selected reached below the tip of the crack.

IV SAMPLE SPECIFICATION

The shot peening specification should include the following controls:

CONTROL	EXAMPLE
1 - Shot size	550
2 - Energy of Impact	.008-.010C Almen Intensity
3 - Complete Cold Work	Peen 3" either side of all welds.
4 - Quality	a. Use method "b" paragraph 6.11 page 11 of MIL-S-13165C to check for coverage. b. Inspect for complete cold work using a black light with 100 watt high intensity bulb which emits long wave ultra-violet radiation in the range of 365° Angstrom units

V REASONS FOR REPEENING (PEENING A SURFACE FOR A SECOND OR MORE TIME).

1 - Relief of beneficial compressive stresses by fire (temperatures above 500°F will reduce the stresses, while temperature above 1000°F will completely eliminate the beneficial compressive stresses).

2 - Yielding of the metal surface as may be caused by impact of a truck during an accident.

3 - Grinding, drilling, machining or welding of a peened detail.

4 - The surface to be peened should be free of paint or rust. Preparation of the surface may be by grinding

APPENDIX B

THINGS TO DO WHEN PLANNING TO SHOT PEEN

1. Introduce controlled shot peening requirements to all parties involved.

NEW CONSTRUCTION	REPAIR	REASON
A. Designer	Consultant	Determine fatigue critical details.
B. Fabricator	Welder	Prepare sample weld specimen.
C. Erector		Avoid tack welding, grinding, drilling, etc. of shot peened surfaces.
D. Certified Shot Peener	Shot Peen	Select automatic peening equipment

2. Write Peening Specification
   A. Select Almen intensity range.
   B. Choose shot size.
   C. Prepare sketches outlining areas to be painted with fluorescent Dyescan tracer.
3. Prepare Fatigue Critical Details

A. Grind or blast (Aluminum oxide or steel) clean if rusty or painted.

B. Nondestructively test (N.D.T.) all fatigue critical welds.

C. Weld with procedures that avoid porosity, slag inclusions, stray arc strikes, etc.

D. Paint on fluorescent dye where indicated on sketches/ specification.

E. Shot peen with MIL-S-13165 controls.

F. Quality control to check for coverage and weld quality.

G. Prepare for painting if needed.

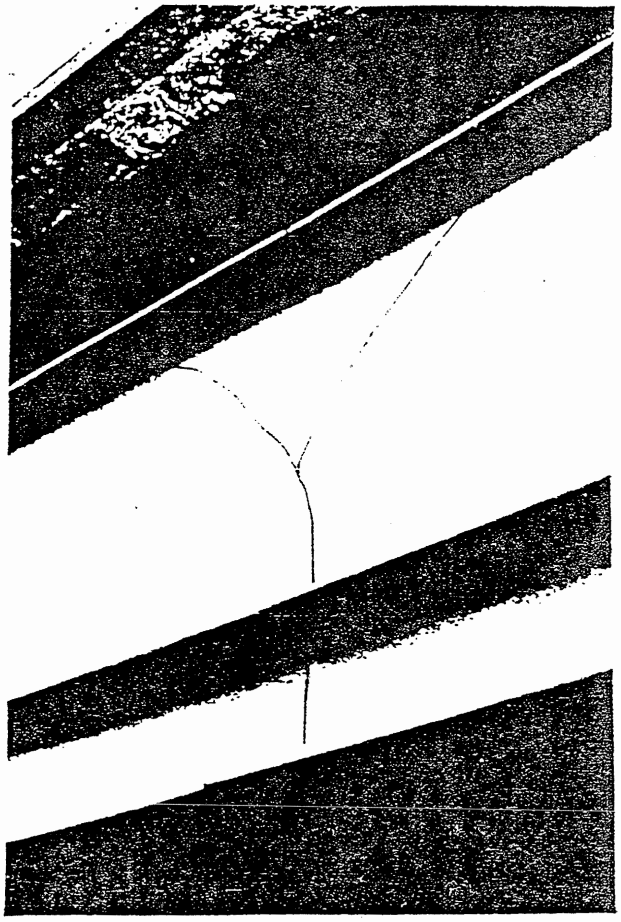

Fig. 1 Fatigue crack initiated at stiffener butt weld joint in a composite bridge girder.

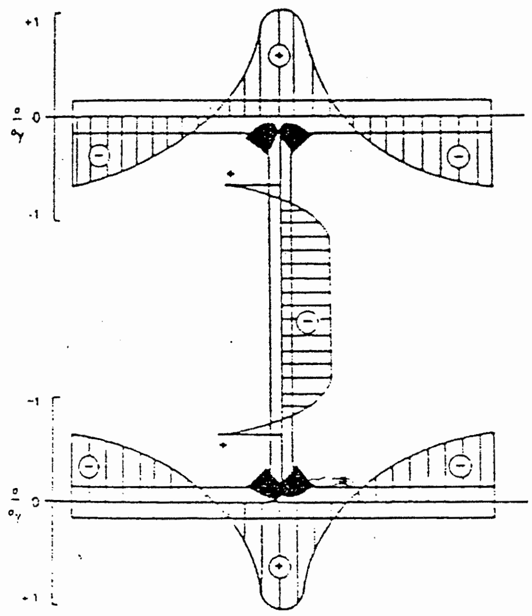

Fig. 2 Residual stresses in welded beam - SAE Design Handbook (2)

σ = residual stress

σ_y = yield strength

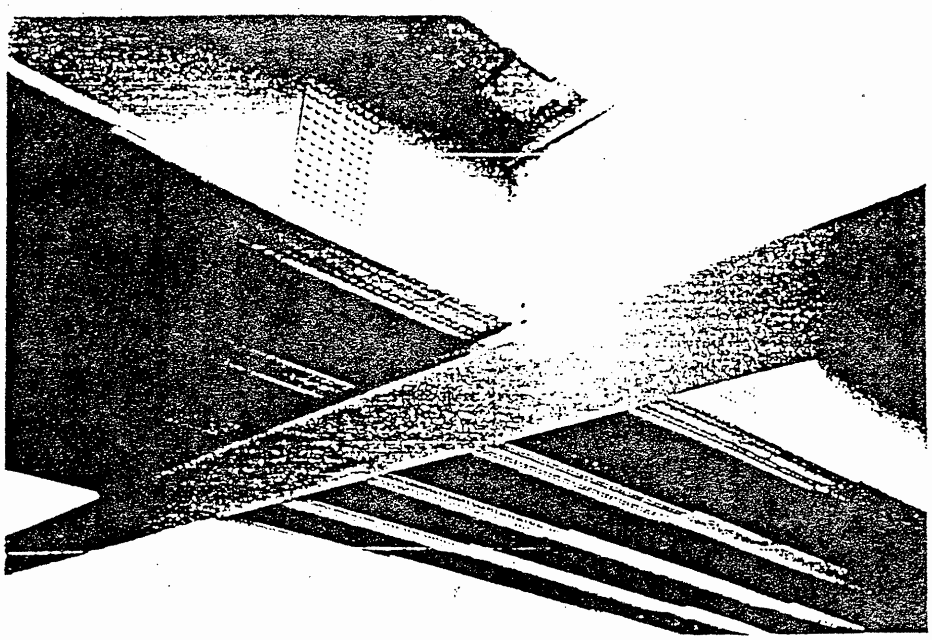

Fig. 3 Box girder design with holes drilled at fatigue crack initiation points.

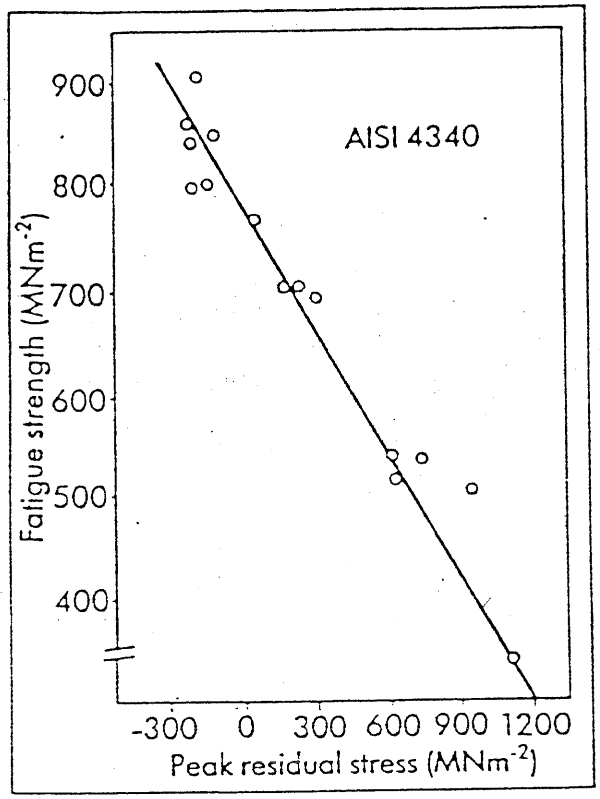

Fig. 4 Correlation between fatigue strength and peak residual stress for AISI 4340 steel.(5)

Fig. 5 Setting up for controlled shot peening of coverplate termination welds at the Passaic Avenue Bridge over New Jersey Route 46.

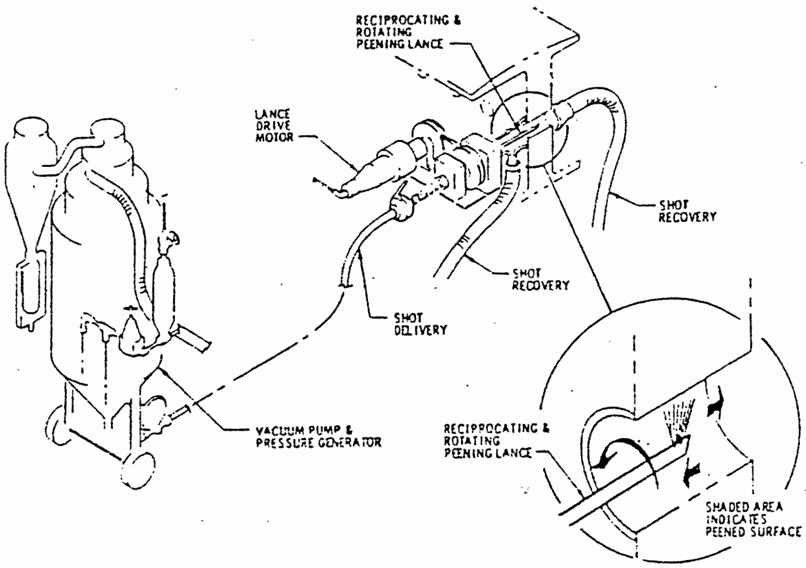

Fig. 6 Typical portable machine for controlled shot peening of holes.