The weld dimensions and welding parameters have been measured in fillet weld tests and these data used to make plots of leg lengths squared versus energy input. Another source of heat input data has been information derived from the deposition rate data, where it has been assumed that all of the metal deposited went into forming an ideal fillet. Where a root opening was present, the leg length was smaller for the same energy input than for the condition of perfect fit-up. The results of these plots are shown in Figure P.4.

For manual covered electrodes with large quantities of iron powder in the covering, a larger fillet size for the same energy is produced. For submerged arc welding, electrode polarity and electrode extensions have a marked effect, as would be expected. For the normal practical range of welding parameters, a single scatter band can be considered and a lower bound curve selected as a basis for welding procedure design.

P.5.6 Application

It should be clear that the proposed methods presuppose a good engineering understanding of the concepts involved as well as a sound appreciation of the influence of the basic factors and their interplay built into the preheat methodology.

Engineering judgement must be used in the selection of the applicable hardness curve and in a realistic evaluation of the restraint level.

The method of measuring effective preheat remains an independent matter and requires separate and continuous attention.

The effectiveness of preheat in preventing cracking will depend significantly on the area preheated and the method used. Since the objective is to retard the cooling rate to allow the escape of hydrogen, a larger preheated area will stay hot longer and be more effective.

P.5.7 Bibliography

1) Coe, F.R. 1973. *Welding Steels Without Hydrogen Cracking*. The Welding Institute, UK.
2) BSI Standard 5135-1974. *Specification for Arc Welding of Carbon and Carbon Manganese Steels*.
3) Ito, F. and K. Bessyo, *A Prediction of Welding Procedures to Avoid HAZ Cracking*. IIW document No. IX-631-69.
4) McParlan, M. and B.A. Graville, 1976. Welding Journal 55, No. 4, Res. Suppl. April 1976, p-92-s.
5) Suzuki, M. *Cold Cracking and its Prevention in Steel Welding*. IIW document No. IXC 1074-78.
6) Teraski et al. Trans. 1979. JWS Vol. 10, No. 1, April.
7) Graville, B.A. Determining Requirements for Preheat. *Technology Focus*, October 1980, Welding Institute of Canada.
8) Yurioka, N., H. Suzuki, S. Oshita, and S. Saito, 1982. *Determination of Necessary Preheating Temperatures in Steel Welding*.
9) Yurioka, N. and T.A. Kasuya, 1995. *Chart Method to Determine Necessary Preheat in Steel Welding*, 1995.
10) Yurioka, N. 2003. *Comparison of Preheat Predictive Methods*.

Annex Q (informative)
Lamellar tearing

Note: *This Annex is not a mandatory part of this Standard.*

Q.1 General

Q.1.1

Lamellar tearing is the separation of the parent or base metal in planes generally parallel to the rolling direction of the plate. The tearing develops in susceptible material as a result of high through-thickness strains. The through-thickness strains are the normal results of weld and base metal shrinkage, especially in restrained joints.

Q.1.2

By definition, lamellar tears always lie within the base metal, generally parallel to the weld fusion boundary. The tear may initiate just outside the visible heat-affected zone and propagate to the root or toe, in which case the tear may be detected visually (see Figure Q.1). Often, however, the tear is subsurface, in which case ultrasonic testing is the most effective method of detection.

Q.1.3

Lamellar tears exhibit a unique step-like appearance which allows them to be distinguished from other forms of cracking. When viewed in section (see Figure Q.2), long terraces parallel to the rolling direction are joined by near vertical, short transverse shear walls. The tear surface is fibrous or woody in appearance, characteristic of a low-ductility fracture. The tear can run along a joint for a considerable distance and have a width approximately equal to the size of the weld.

Q.2 Susceptibility of lamellar tearing

Q.2.1

The susceptibility of a particular carbon or low-alloy steel plate to lamellar tearing is primarily dependent upon its local through-thickness ductility. Generally, the type, shape, and distribution of nonmetallic inclusions, mainly of the manganese sulphide, manganese silicate, and oxide types, control the reduction in ductility. The inclusion content and morphology depend upon many factors including the steel-making process, deoxidation and final sulphur controls, ingot pouring, and rolling practices.

Q.2.2

It is important to recognize that only a small percentage of steel plates are susceptible to tearing, even though all steels contain inclusions. Essentially, the extent of elongation of the inclusions close to the plate surface during rolling dictates the susceptibility of the material. Only a small percentage of the potentially susceptible plates will be incorporated into weldments at critical locations.

Q.2.3

For tearing to occur, three conditions must be satisfied:

a) the base metal must be susceptible to tearing at the joint, i.e., it must have poor through-thickness ductility;
b) the weld orientation must be such that strains are directed through the plate thickness; and

c) strains due to weld metal shrinkage must be developed and potentially enhanced due to restraint or member rotation.

Q.3 Selection of material

Selection of the appropriate material and configuration of the joint is normally the responsibility of the designer. If these cannot be changed or improved, the Fabricator should be made aware by the designer of the locations within the structure where the combinations are critical.

Q.4 Fabrication technique

Fabrication techniques that reduce the probability of lamellar tearing can be adopted:

a) selection of a structurally acceptable, lower-strength, welding consumable;
b) symmetrical deposition of the weld passes to balance double-sided joints and minimize strains (see Figure Q.3);
c) prior buttering of the joints with a ductile layer (see Figure Q.4) or in situ buttering;
d) selecting a joint geometry to minimize through-thickness strains (see Figures Q.5 and Q.6);
e) removal and replacement of the susceptible material with ductile weld metal (see Figure Q.7);
f) the use of high-deposition, low-hydrogen consumables;
g) the use of fillet or partial joint penetration groove welds in preference to complete joint penetration (see Figure Q.8);
h) the judicious use of preheat providing that additional strain is not created; and
i) selection of a fabrication sequence to minimize the restraint strains at the critical location.

Q.5 Inspection

Q.5.1

Normal visual and magnetic particle examination appears adequate for detection of tears that reach the surface in joints where the risks due to lamellar tearing are small. For members and joints that are critical to the overall integrity of the structure, ultrasonic examination of the joint after welding should be specified.

Q.5.2

While ultrasonic examination methods are effective in locating plate and weld defects, it is often difficult to distinguish true lamellar tears from inclusion bands and other forms of cracking. In order to distinguish lamellar tears from pre-existing defects, the area of the weld should be ultrasonically inspected prior to fabrication. Final ultrasonic examination should be delayed for at least 36 h after welding to allow maximum restraint conditions to develop.

Q.6 Repairs

Q.6.1

Standards for acceptance of lamellar tearing should be considered prior to fabrication since the removal and repair of minor noncritical tears may do more harm than good. The repair of lamellar tears can be difficult, time-consuming, and costly. The additional restraint conditions that often result from weld repairs can cause additional deeper tearing to occur, compounding the original problem.

Q.6.2
The fundamental repair procedure involves gouging out the torn area and rewelding. The use of the same joint geometry and welding procedures under conditions of probable higher restraint could simply result in new tears. As a result, the techniques noted earlier to minimize the probability of tearing should be carefully reviewed. In situ butter layers of a low yield strength weld metal are generally very effective in repair welding.

Q.7 Bibliography
Much has been written about lamellar tearing. The following references are a sampling of sources of additional information on this topic:

American Institute of Steel Construction. 1973. Commentary on Highly Restrained Welded Connections. *Engineering Journal*, Third Quarter.

Farrar and Dolby. 1972. *Lamellar Tearing in Welded Steel Fabrication*. The Welding Institute.

Kaufmann, Pense, and Stout. 1981. An Evaluation of Factors Significant to Lamellar Tearing, *The Welding Journal*, March.

Kaufman, I.J., and Stout, R.D. 1983. The Toughness and Fatigue Strength of Welded Joints with Buried Lamellar Tears, *The Welding Journal*, November.

Ship Structure Committee SSC-290 Project SR-1250. 1979, *Significance and Control of Lamellar Tearing of Steel Plate in the Shipbuilding Industry*. Department of Transportation, US Coast Guard.

USS Technical Report 10-F-002 (018.5). 1975. *Lamellar Tearing in Plate Steels* (A Literature Survey).

Westhoff, J.R. 1975. *Welding Design and Fabrication*, January.

Figure Q.1
Typical location of lamellar tears
(See Clause Q.1.2.)

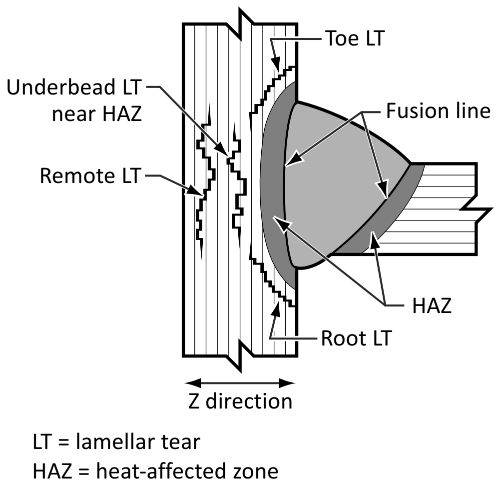


Figure Q.2
Step-like appearance of lamellar tears
(See Clause Q.1.3.)

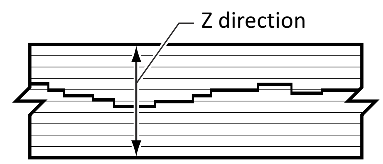


Figure Q.3
Symmetrical deposition of weld passes
(See Clause Q.4.)

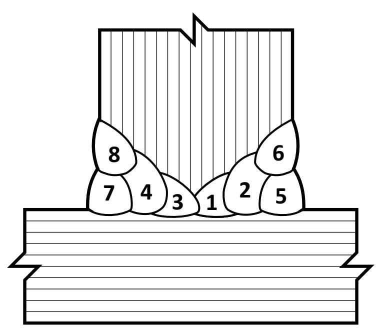


Figure Q.4
Buttering of the joint
(See Clause Q.4.)

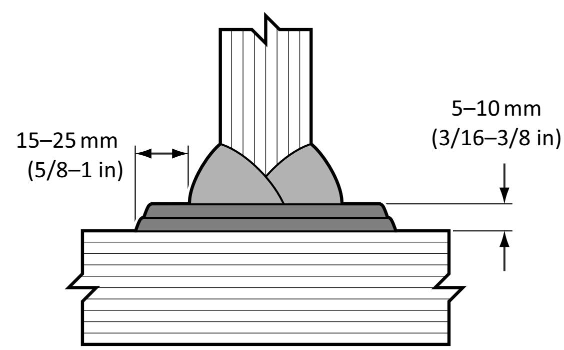


Figure Q.5
Selecting a joint to minimize through thickness strains
(See Clause Q.4.)

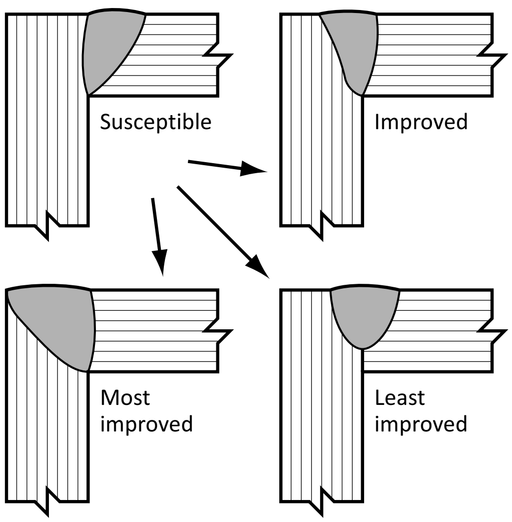


Figure Q.6
Reducing the weld size by placing it in the thinner plate
(See Clause Q.4.)

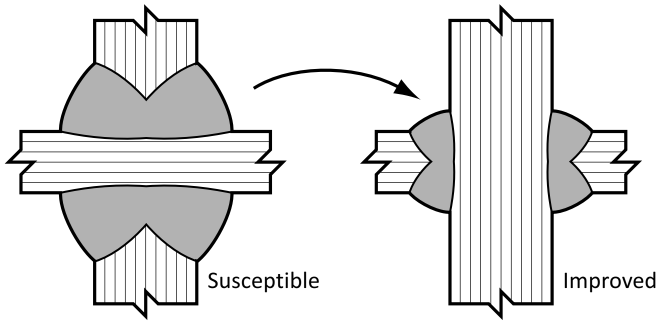


Figure Q.7
Buttering of a joint by removal of susceptible material
(See Clause Q.4.)

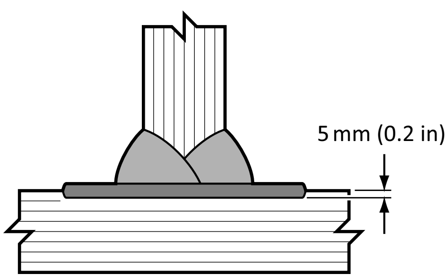
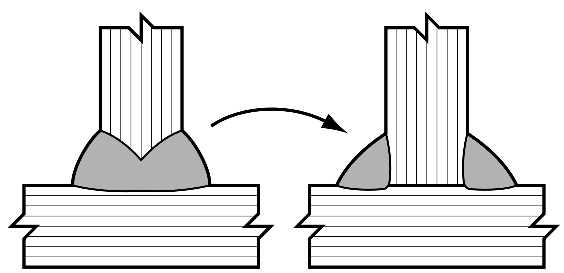


Figure Q.8
Use of fillet welds in preference to complete joint penetration groove welds
(See Clause Q.4.)



Annex R (informative)
The fatigue life of structures and postweld methods of fatigue life enhancement

Note: *This Annex is not a mandatory part of this Standard.*

R.1 Using the basic S-N equation

Note: *See Clause 12.3.4.6.5.*

R.1.1

The S-N equation of Clause 12.3.4.6.5 is repeated here for reference:

$$F_{sr} = \left(\frac{\gamma}{N_c}\right)^{\frac{1}{3}}$$

where

F_{sr} = constant amplitude fatigue stress range resistance of a member or detail

γ = the fatigue life constant for a detail (as given in Table 12.3 and determined from Table 12.4)

N_c = number of stress cycles

R.1.2

As an example of the use of the equation, consider a built-up plate girder, which is to contain web to flange welds consisting of continuous partial penetration groove welds parallel to the direction of applied stress. From Table 12.4, the detail category for live-load induced fatigue is B1 (Example 4). From Table 12.3 the fatigue life constant γ is 2.00 E+12. The girder is to be subjected to a constant amplitude live-load induced stress 72 times per day for 350 days per year. The design life is to be 50 years, resulting in 1 260 000 cycles of load application.

From the equation, the resulting allowable specified live-load induced stress range is

$$F_{sr} = \left(\frac{2.00E+12}{126E+4}\right)^{\frac{1}{3}} = 116.64\ MP$$

In Imperial units, the following result is obtained, using γ = 6.1E+9

$$F_{sr} = \left(\frac{6.1E+9}{126E+4}\right)^{\frac{1}{3}} = 16.92\ ksi$$

R.1.3

It is decided that a cover plate is required on the proposed built-up girder and that the cover plate will be wider than the flange, without end welds. The detail category is E1 (Example 7), and the fatigue life constant γ is 1.28 E+11. The cover plate is initially extended to a location where the live-load induced stress range in the girder is 60 MPa. Has the design life of the girder been reduced?

The equation can be rearranged as

$$N = \frac{\gamma}{(F_{SR})^3} = \frac{1.28E+11}{(60)^3} = 592593\ cycles$$

or in Imperial,

$$N = \frac{\gamma}{(F_{SR})^3} = \frac{3.9E+8}{(8.70)^3} = 592292\ cycles$$

The fatigue life is therefore significantly reduced. To maintain the required 1 260 000 load cycles, the cover plate must be terminated on the built-up girder at a location where the actual specified live-load induced stress range is

$$F_{sr} = \left(\frac{\gamma}{N}\right)^{1/3} = \frac{1.28E+11}{(126E+4)^{1/3}} = 46.66\ MPa$$

or in Imperial,

$$F_{sr} = \left(\frac{\gamma}{N}\right)^{1/3} = \frac{3.9E+8}{(126E+4)^{1/3}} = 6.76\ ksi$$

R.1.4

The equation can be rearranged to show the magnitude of change produced in one variable as a consequence of the change in another variable for a particular fatigue life constant:

$$\frac{N2}{N1} = \left(\frac{S1}{S2}\right)^3 \text{ or } \frac{S2}{S1} = \left(\frac{N1}{N2}\right)^{1/3}$$

Consider, for example, the consequence on fatigue life of reducing the stress range by 50%:

$$N2 = N1\left(\frac{S1}{0.5S1}\right)^3 = N1(2)^3 = 8N1$$

Or consider the required reduction in stress to increase the fatigue life by a factor of 2.5:

$$S2 = S1\left(\frac{N1}{2.5N1}\right)^{1/3} = S1(0.4)^{1/3} = 0.737S1$$

R.2 Application of Miner's Rule for cumulative damage

Note: *See Clause 12.3.4.6.7.*

R.2.1

The web of a crane girder contains a transversely loaded fillet welded attachment with welds parallel to the direction of primary stress in the girder. There is a transition radius on the attachment but the welds are not ground smooth. From Example 12 in Table 12.4, the detail category is E. From Table 12.3, the fatigue life constant γ is 3.61 E+11 (1.1 E+9) and the threshold stress range is 31 MPa (4.5 ksi). The girder carries a small crane that makes numerous trips in one direction loaded and return trips empty. The girder also carries a larger heavier crane which also passes over the girder loaded in one direction and empty in the other direction. After 26 years of use, it is estimated that the live-load induced stress ranges and cycles at the web attachment for the two cranes are

Stress range	Estimated cycles
30 MPa (4.35 ksi)	2 100 000
14 MPa (2.03 ksi)	2 100 000
85 MPa (12.33 ksi)	180 000
53 MPa (7.69 ksi)	180 000

R.2.2 Cumulative fatigue damage to the crane girder

Using the equation $N = \gamma / (F_{sr})^3$, the following are obtained:

Stress range	Estimated cycles, n	Allowable cycles, Na	Estimated/ allowable, n/Na
30 MPa* (4.35 ksi)	2 100 000	14 279 835	0.147
14 MPa* (2.03 ksi)	2 100 000	645 192 479	0.003
85 MPa (12.33 ksi)	180 000	587 828	0.306
53 MPa (7.69 ksi)	180 000	2 424 820	0.074

* *Since the stress range is less than the threshold stress range (for F_{srt} see Table 12.3), use $Na = \gamma'/(F_{sr})^5$ where γ' = 3.47E+14 (2.2E+10)*

Using Miner's rule from Clause 12.3.4.6.7, the cumulative fatigue damage factor at the detail is $\Sigma(n/N_a) = 0.147 + 0.003 + 0.306 + 0.074 = 0.530$

R.2.3 Anticipated fatigue life of the crane girder

Based on the Linear Cumulative Damage Rule, the estimated fatigue life of the girder is thus

26/0.530 = 49.06 years. Since the girder is 26 years old, the remaining life is 49.06 – 26 = 23.06 years.

R.3 Postweld methods of fatigue life enhancement

Note: *See Clauses 9.5.1 and 12.3.4.8.*

R.3.1

The following postweld methods of reconditioning welded details may be used when written procedures have been approved by the engineer:

a) toe grinding — grinding weld toes only with a burr or pencil grinder;
b) peening — shot peening of weld surface, or hammer peening of weld toes;
c) TIG dressing* — remelting the weld toe with the heat from a GTAW arc (no filler metal used);
d) toe grinding plus hammer peening — used together, the benefits are cumulative;
e) ultrasonic impact technology (UIT) — plastic deformation of material at the weld toes and introduction of compressive stresses [also commonly referred to as high frequency mechanical impact (HFMI) treatment].

* *"TIG dressing" is the industry-adopted terminology for this GTAW technique.*

R.3.2

When properly administered, these reconditioning methods may be used to enhance the fatigue life of existing structures, particularly when the applied stress is normal to the axis of the weldment. The various techniques listed affect fatigue life only from the point of view of failure from the weld toe. However, the possibility of fatigue crack initiation from other features of the weld (e.g., the root area) should not be overlooked.

Typical applications for these techniques include the repair of fatigue cracks and the extension of fatigue life of existing structures and equipment.

R.3.3 Discussion

R.3.3.1

Welded joints create severe stress concentrations. Research at The Welding Institute (TWI), Cambridge, England, has identified a line of microscopic slag intrusions along the toes of all welds made by all arc processes except gas tungsten arc welding (GTAW). All processes, however, were found to produce some degree of undercut at the toe, notwithstanding ideal weld profiles (Figure R.1).

The practical implication is that all welds have a pre-existing discontinuity in the form of either microscopic undercut or slag intrusions, or both. Normal inspection methods cannot detect these discontinuities, which in any case are unavoidable when using existing technology [*Maddox, 1992a*; Commission IIW Working Group 2, 1993; Maddox, 1992b (*Ch. 1, 2*)].

R.3.3.2

In plain material, fatigue life consists of both crack initiation and propagation. In weldments, however, it must be assumed that crack-like discontinuities already exist. Therefore, the fatigue life of welds is spent solely in crack propagation. This, along with residual tensile stresses at or near the yield point, is the essential reason why weldments can endure fewer cycles to fatigue failure than a similarly loaded plain material (Figure R.2).

R.3.3.3

Fatigue life enhancement can be obtained by dressing the weld toes. The small pre-existing discontinuities are either removed or the sharp openings dulled (Figure R.3). Toe grinding and TIG dressing extend fatigue life by restoring a crack initiation phase. Peening or HFMI treatment, by the introduction of a compressive stress, retards the rate of crack propagation. The resulting weld profile also complements the overall joint resistance to fatigue cracking by reducing the geometric stress concentration. When these pre-existing toe discontinuities are perpendicular to the applied stress, fatigue life enhancement methods are most effective (Figure R.4) [*Maddox 1992b* (Ch. 4)].

R.3.4 Toe grinding

Toe grinding is done along the centreline of the weld toe. The recommended tools include a high speed grinder for use with a tungsten carbide burr. The tip radius is scaled to the plate thickness in accordance with Table R.1. These radii are the minimum recommended; larger sizes may prove more beneficial.

Grinding is carried out to a minimum depth of 0.8 to 1.0 mm (0.03 to 0.04 in) below the plate surface or approximately 0.5 to 0.8 mm (0.02 to 0.03 in) below the deepest visible undercut to a maximum total depth of 2 mm (1/16 in) or 5% of the plate thickness, whichever is greater. The axis of the burr is at approximately 45° to the main plate (see Figure R.5). The angle of the burr axis is a maximum of 45° to the direction of travel, to ensure that the grinding marks are nearly perpendicular to the weld toe line (parallel to the direction of stress). The ends of longitudinally stressed welds require special care to be effective (see Figure R.6). The finishing pass should be light to obtain a good surface finish. Check visually and with magnetic particle or dye penetrant inspection for any remaining undercut or other discontinuities. [For additional information on toe-grinding, see *Maddox 1992a, Haagensen, Haagensen, Maddox 1992b*, (Ch. 2, 8.)]

R.3.5 Hammer peening

R.3.5.1

Hammer peening applies to steels with yield strengths up to 800 MPa (115 ksi) and thickness not less than 10 mm (3/8 in). Steel hammer bits should have approximately hemispherical tips with diameters between 6 and 12 mm (1/4 and 1/2 in). The indentation is centred on the weld toe so that metal on each side (both weld metal and parent material) is deformed, resulting in a smooth surface free from obvious individual blows. The hammer should be held at 45° to the plate surface and approximately perpendicular to the direction of travel.

R.3.5.2

The indentation in mild steel [yield strength up to 250 MPa (36 ksi)] should be approximately 0.5 mm (0.02 in); in medium-strength steel [yield strength between 250 and 450 MPa (36 and 65 ksi)] 0.25 mm (0.01 in); and in high-strength steel [yield strength between 450 and 800 MPa (65 ksi and 115 ksi)] 0.1 mm (0.004 in) (see Figure R.7). These depths are roughly equivalent to four peening passes. The weld should be checked visually and with magnetic particle or dye penetrant inspection prior to peening. [*Maddox, 1992; Haagensen; Maddox 1992b (Ch. 2, 8, 10.)*] The benefit of hammer peening is derived from the introduction of compressive residual stresses; thus, it is critical to ensure that nothing that will cause stress relief (e.g., postweld heat treatment) be performed after peening. Also, hammer peening should be applied when the joint is in place and carrying dead-load. In the case of welds inspected after hammer peening is performed, if the combined initial undercut depth plus depth of the peening indent exceeds the limit in the undercut depth (Item h) specified in Clause 12.5.4.2, engineering judgement should be used to determine if the weld is acceptable.

R.3.6 TIG dressing

TIG (GTAW) dressing consists of remelting the existing weld metal to a depth of approximately 2 mm (1/16 in) along the weld toe without the addition of filler metal. The weld surface should be free from rust, slag, and mill scale. The tip of the electrode must be kept sharp and clean. The tip must be located horizontally 0.5 to 1.5 mm (0.02 to 0.06 in) from the weld toe (see Figure R.8). Where toughness of the heat-affected zone might create problems, a modified technique using a second tempering pass may be used.

R.3.7 Toe grinding plus hammer peening

Toe grinding followed by hammer peening inhibits fatigue crack initiation and the rate of crack propagation. Thus, for critical joints, this combined treatment offers superior resistance to fatigue failure. The weld surface should be checked visually and by magnetic particle for surface discontinuities prior to peening. During peening operations, visually check after each pass. (See *Hangensen; Improving the Fatigue Performance of Welded Joints; Takenouchi et al*.)

