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WELD DETAIL FATIGUE LIFE IMPROVEMENT TECHNIQUES

SHIP STRUCTURE COMMITTEE

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Fatigue cracks in steel ships often occur at welded joints where stress concentrations due to the joint geometry are relatively high and the fatigue strength of the weld is reduced in comparison to that of the base metal. This becomes more critical in ships built of High Strength Steels (HSS) because the fatigue strength of steel in the as-welded condition does not increase in proportion to the yield or tensile strength. In many cases, the fatigue performance of severely loaded details can be improved by employing good detail design practices, for example by upgrading the welded detail class to one having a higher fatigue strength. In some cases, however, there may be no better alternatives to the detail in question and modification of the detail may not be practicable. As an alternative to strengthening the structure at a considerable increase in costs, procedures which reduce the severity of the stress concentration at the weld, remove imperfections, and / or introduce local compressive stresses at the weld can be used for improvement of the fatigue life. Similarly, these fatigue improvement techniques can be applied as remedial measures to extend the fatigue life of critical welds that have failed prematurely and have been repaired.

To date, weld fatigue life improvement techniques have been successfully applied in several industries. While there has been increasing interest in the application of fatigue life improvement techniques to ship structures, at present there is a lack of guidance on the use of such techniques for design, construction and repair. Hence the key elements of this project were to compile available data on fatigue life improvement techniques, assess the feasibility and practicality for their application to ship details, identify gaps in the technology, and finally to recommend design, construction and repair requirements.

ROBERT C. NORTH
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

Fatigue cracks in steel ships often occur at welded joints where stress concentrations due to the joint geometry are relatively high and the fatigue strength of the weld is reduced in comparison to that of the base metal. This becomes more critical in ships built of High Strength Steels (HSS) because the fatigue strength of steel in the as-welded condition does not increase in proportion to the yield or tensile strength. In many cases, the fatigue performance of severely loaded details can be improved by employing good detail design practices, for example by upgrading the welded detail class to one having a higher fatigue strength. In some cases, however, there may be no better alternatives to the detail in question and modification of the detail may not be practicable. As an alternative to strengthening the structure at a considerable increase in costs, procedures which reduce the severity of the stress concentration at the weld, remove imperfections, and / or introduce local compressive stresses at the weld can be used for improvement of the fatigue life. Similarly, these fatigue improvement techniques can be applied as remedial measures to extend the fatigue life of critical welds that have failed prematurely and have been repaired.

To date, weld fatigue life improvement techniques have been successfully applied in several industries. While there has been increasing interest in the application of fatigue life improvement techniques to ship structures, at present there is a lack of guidance on the use of such techniques for design, construction and repair. Hence the key elements of this project were to compile available data on fatigue life improvement techniques, assess the feasibility and practicality for their application to ship details, identify gaps in the technology, and finally to recommend design, construction and repair requirements.

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(Approximate conversions to metric measures)

To convert from	to	Function	Value
LENGTH			
inches	meters	divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
inches^2 feet^2	centimeters^2 meters^2	multiply by	1.9665
inches^2 feet^2	centimeters^3	multiply by	196.6448
inches^4	centimeters^3	multiply by	16.3871
MOMENT OF INERTIA			
inches^2 feet^2	centimeters^2 meters	divide by	1.6684
inches^2 feet^2	centimeters^4	multiply by	5993.73
inches^4	centimeters^4	multiply by	41.623
FORCE OR MASS			
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long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
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kilo pounds/inch^2	mega Newtons/meter^2 (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tons	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo pound/inch^2 inch^{½}(ksi$\sqrt{\text{in}}$)	mega Newton MNm$^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	Joules/mm^2	multiply by	0.1753
kilo pound/inch	kilo Joules/m^2	multiply by	175.3

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1.0 INTRODUCTION

1.1 BACKGROUND

Ship structures experience cyclic loadings which can cause fatigue cracking in the structural members and details of the ship if they are inadequately designed, constructed or maintained. Serious cases of fatigue cracks can lead to major damage or even to catastrophic failure of the hull structure. Even if fatigue cracking in ship hulls is usually not a serious safety problem, the costs of inspections and repairs, and the consequences of damage due to water ingress or oil leakage can be high.

Fatigue cracks in steel ships often occur at welded joints in the ship structure where stress concentrations due to the joint geometry are relatively high and the fatigue strength of the weld is reduced in comparison to that of the base metal. This becomes more critical in ships built of High Strength Steels (HSS) because the fatigue strength of steel in the as-welded condition does not increase in proportion to the yield or tensile strength. As a result, fatigue of welded details can be a limiting factor for the design of more efficient ship structures.

In many cases, the fatigue performance of severely loaded details can be improved by employing good detail design practices, for example by upgrading the welded detail class to one having a higher fatigue strength. In some cases, however, there may be no better alternatives to the detail in question and modification of the detail may not be practicable. As an alternative to strengthening the structure at a considerable increase in costs, procedures which reduce the severity of the stress concentration at the weld, remove imperfections, and / or introduce local compressive stresses at the weld can be used for improvement of the fatigue life. Similarly, these fatigue improvement techniques can be applied as remedial measures to extend the fatigue life of critical welds that have failed prematurely and have been repaired.

To date, weld fatigue life improvement techniques have been successfully applied to offshore structures, steel bridges, rail cars and, to a limited extent, ship structures. While there has been increasing interest in the application of fatigue life improvement techniques to ship structures, at present there is a lack of guidance on the use of such techniques for design, construction and repair. Hence the key elements of this project are to compile available data on fatigue life improvement techniques, assess the feasibility and practicality of their application to ship details, identify gaps in the technology, and finally to recommend design, construction and repair requirements.

1.2 OBJECTIVES AND SCOPE

The objectives of this project were to:

a) Organize and research existing literature on fatigue life improvement techniques applicable to welded ship details;

b) Evaluate the feasibility, practicality and costs associated with applying the various fatigue life improvement techniques to the construction of new ships and to the repair of fatigue critical details in existing ships. The techniques should be evaluated in terms of fatigue performance improvement, practicality for construction and repair of various ship structural details including potential for automation and / or linking to standard welding equipment, and costs and time penalties associated with the techniques; and

c) Determine optimal procedures and parameters for application of those techniques that offer the most potential to provide reliable and cost-effective fatigue life enhancement for ship structural details. Suggest improvements and recommend any additional testing or development work of candidate procedures required to fill gaps in the technology or data.

1.3 OVERVIEW OF REPORT

This report is organized into five sections starting with Section 1, the Introduction.

Section 2 reviews the fatigue performance of welded details in ship structures and, in particular, discusses the physical mechanisms by which the fatigue strength of welded joints is much reduced compared to that of un-welded steel. Section 2 concludes with a discussion of the various approaches that can be used to improve the fatigue strength of welded joints including better design of details, improved welding processes, and weld fatigue improvement techniques, the latter of which is the primary topic for this report.

Section 3 provides a general review of various techniques that have been developed to improve the fatigue strength of welds including machining methods, remelting methods, special welding techniques, peening methods, overloading treatments and thermal methods. A comparison of the relative improvement performance, costs, and practical aspects is presented, and the potential for application to ships is assessed.

Section 4 provides detailed guidance on the use of the three post-weld improvement techniques that, based on the assessment, were determined to offer the best potential for ship applications. These are Weld Toe Grinding, Tungsten Inert Gas (TIG) Dressing, and Hammer Peening. Guidance is given towards the types of details that can benefit from the application of these techniques, the degree of improvement in fatigue strength or life that can be achieved, inspection and quality control considerations, and costs. Detailed procedures for application of these techniques are provided in data sheets presented in the Appendices.

Section 5 summarizes the main conclusions and recommendations of this work, and provides recommendations for future research towards the development and enhancement of weld fatigue improvement technology for ship applications.

2.0 FATIGUE OF WELDED SHIP STRUCTURE DETAILS

2.1 FATIGUE IN SHIP STRUCTURES

Fatigue may be defined as the process of cycle accumulation of damage under fluctuating stresses and strains. An important feature is that the load is not large enough to cause immediate failure but instead failure occurs after the damage accumulated has reached a critical level. Ship structures experience cyclic stress variations caused by seaway motions, wave loading, dynamic effects such as hull girder whipping, springing, machinery and hull vibration, and by changes in cargo distributions. These cyclic stresses can cause fatigue cracking in the structural members and details of the ship if they are inadequately designed, constructed or maintained. Serious incidents of cracks involving primary or secondary structures can pose a direct threat to the safety and operational capability of a ship. So-called nuisance cracks of internal ship structure pose less of a threat to safety, but their frequency over the lifetime of a ship can add up to a significant element of the overall maintenance and repair costs for the ship structure.

A number of studies concerning the in-service fatigue performance of structural details on commercial and military ships have been published. Fatigue critical locations in ships have been identified in a survey of structural details by Jordan et al. in SSC-272 (1978) and SSC-294 (1980). Stambaugh and Wood (1987) summarize fatigue critical locations for special details that may lead to fracture. Heyburn and Riker in SSC-374 (1994) reviewed fatigue problems in High Strength Steel (HSS) ship structures. Clarke (1991) and Kirkhope et al. (1994) have reviewed fatigue cracking experience in naval ships.

Details of tankers that have been identified as being particularly prone to fatigue cracking include:

- intersections of longitudinal stiffeners (particularly side shell longitudinals) with transverse structure (e.g., transverse web frames and bulkheads); and
- bracketed end connections of primary and secondary supporting elements such as deck and bottom longitudinals.

Fatigue prone areas in bulk carriers include:

- hatch corners, coamings and bracketed connections between hold frames and ballast tanks;
- the intersections of transverse corrugated bulkheads with top-side structure; and
- intersections of inner bottom plating with hopper plating.

Additional areas that are prone to cracking of a less serious nature include weldments for tripping brackets and stiffeners. Figures 2.1 and 2.2 summarize typical examples of fatigue cracking problems in ship structural details.

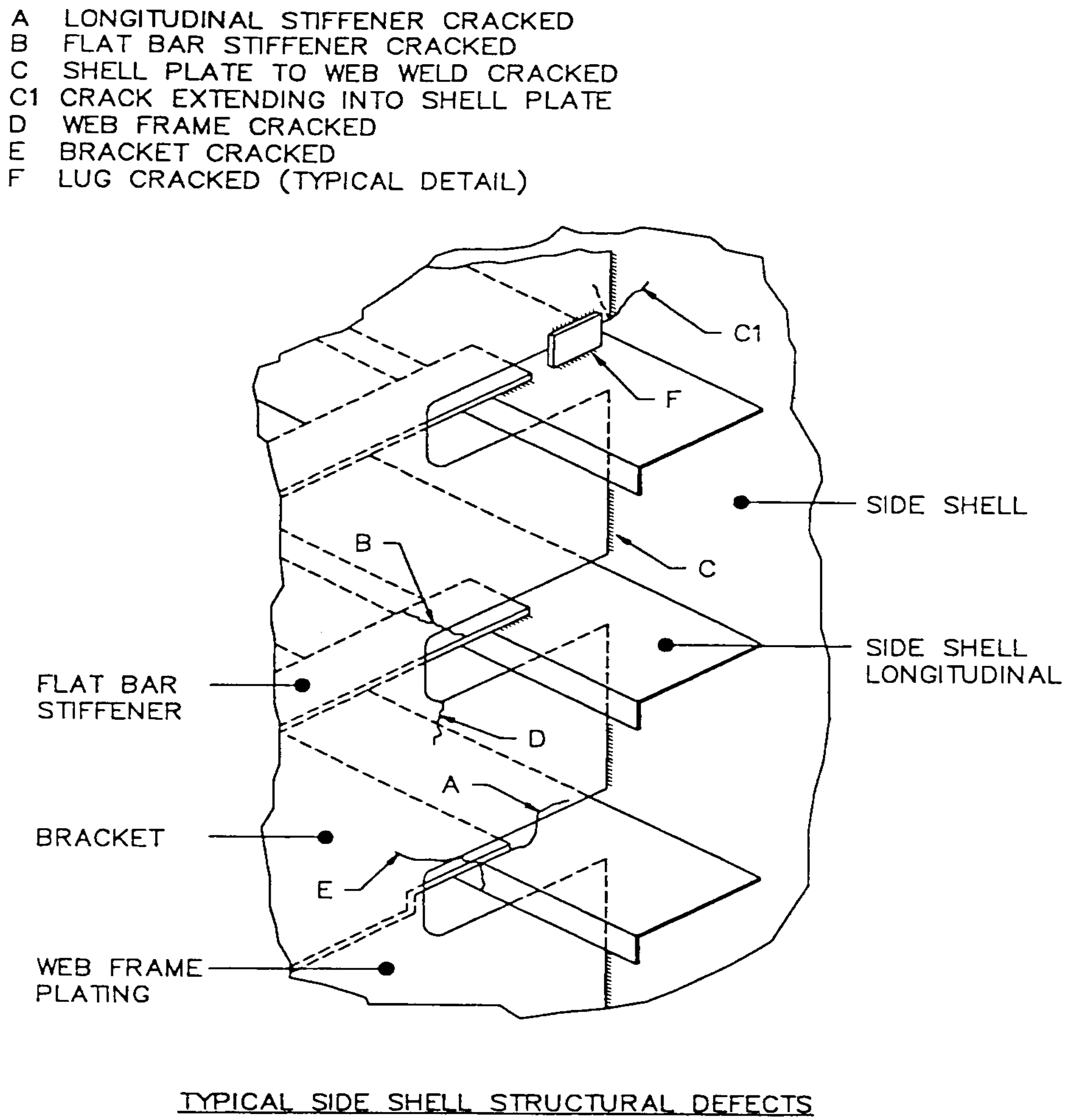

Figure 2.1 Typical Example of Fatigue Cracking In Ship Structural Details (Stambaugh et al., 1994)

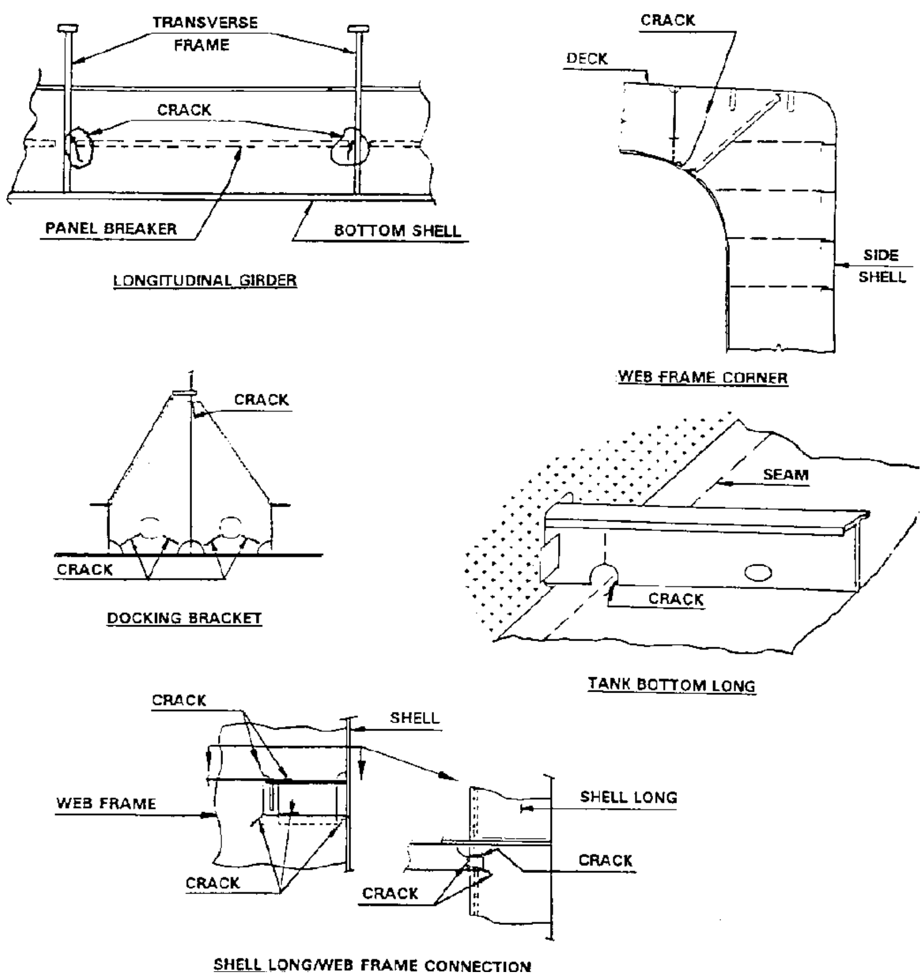

Figure 2.2 Typical TAPS Tanker Cracking Problems (Heyburn and Riker, 1994)

It is apparent from the above discussion that welded details in ship structures represent a particular weakness with regards to fatigue strength. In order to appreciate how the fatigue strength of a welded joint can be improved, it is important to understand the significant features of welds in relation to fatigue and their consequences. The remaining sections of this chapter review the primary factors influencing the fatigue strength of welded joints, and the general approaches that can be used to improve the fatigue performance of welded joints in ship structures.

2.2 FATIGUE STRENGTH OF WELDED JOINTS

The fatigue strength of a structural component may be represented in terms of the S-N curve which plots the number of cycles to failure verses the cyclic stress range. The presence of a weld in a member can drastically reduce its fatigue strength as illustrated in Figure 2.3 which compares the S-N curves of welded connections with those of notched and un-notched steel plate. The plate with a hole suffers a relatively modest reduction in fatigue strength while the high cycle fatigue strength of the welded joint is reduced to about 10% of the fatigue strength of the base material.

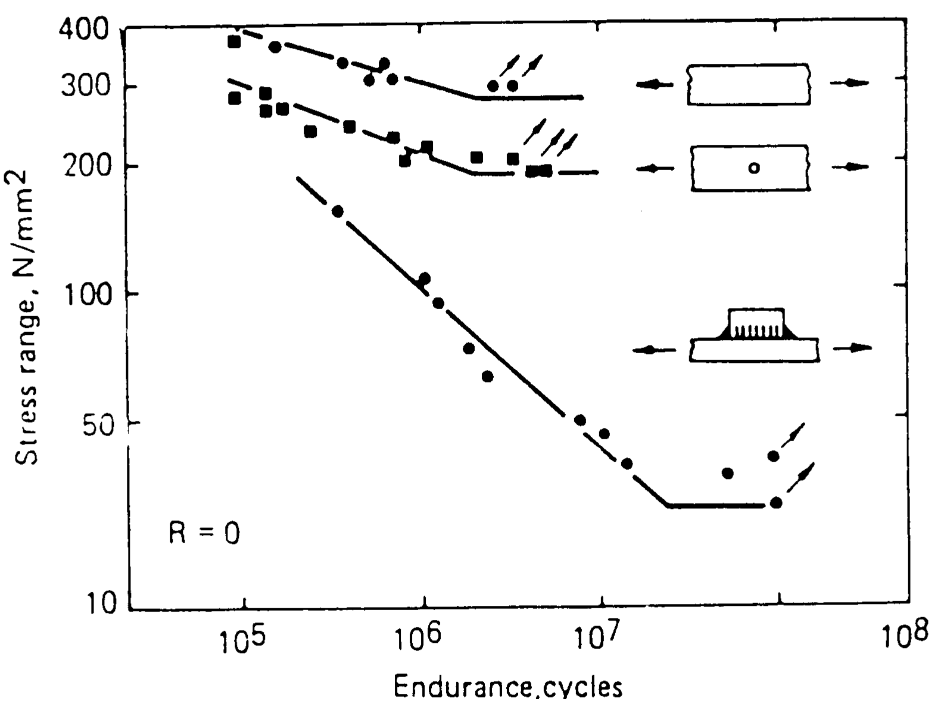

Figure 2.3 Comparison Between Fatigue Strengths of Plain Steel Plate, Notched Plate, and Plate with Fillet Welded Attachment (Maddox, 1983)

Figure 2.4 compares the fatigue strength of steel plate at 10^6 cycles as a function of the ultimate tensile strength of the steel. In this figure, it can be seen that the fatigue strength of steel plate and notched plate increases with tensile strength, while the fatigue strength of welded joints is independent of the tensile strength. The use of High Strength Steels (HSS)[1] in the construction of ships can potentially lead to a significant reduction in the weight of the structure, and therefore in the subsequent build and operating costs. This reduction is achieved through generally lighter scantlings and higher permissable design stresses, but results in correspondingly higher operational fatigue stresses. The low fatigue strength of welded joints is therefore normally a limiting factor in the design of more efficient ship structures using HSS.

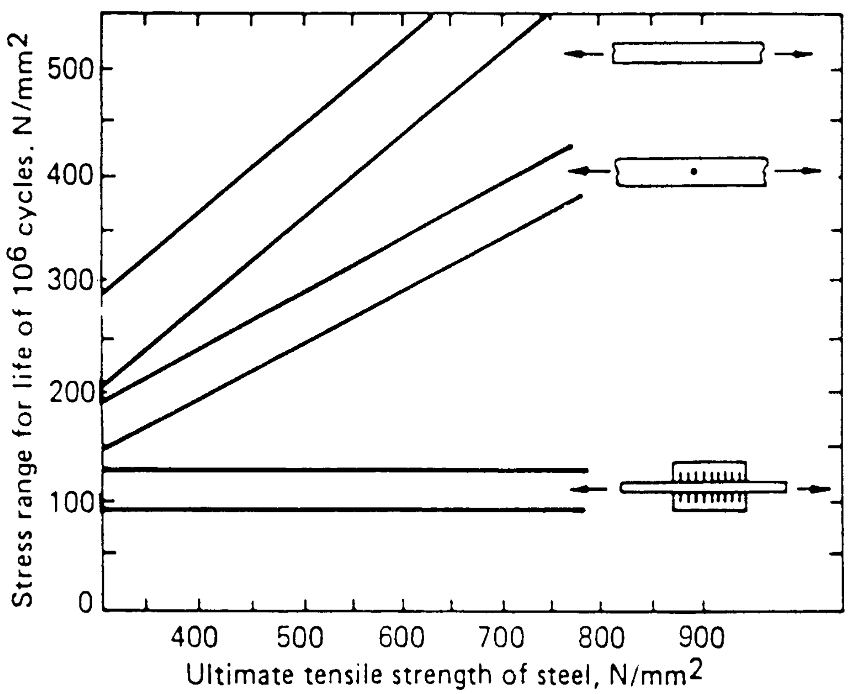

Figure 2.4 Effect of Tensile Strength on Fatigue Strength of Steel (Maddox, 1983)

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[1] HSS in the context of ship construction and Classification Society rules generally have a minimum specified yield strength of up to 390 MPa (56 ksi) compared to conventional Mild Steels (MS) with yield strengths of 235 MPa (34 ksi). Older higher strength grades, exemplified by HY80 (550 MPa / 80 Ksi yield) and T1 (ASTM A514, 690 MPa / 100 ksi yield) are most commonly used in military ship applications. Newer grades of High Strength Low Alloy (HSLA) and Thermo Mechanical Controlled Process (TMCP) steels possess excellent weldability characteristics with yield strengths in excess of 450 MPa (65 ksi).

There are several physical mechanisms that contribute to the reduction in fatigue strength in welded joints. The main mechanisms include:

- Presence of initial crack-like defects;
- Stress concentration at the weld toe; and
- Residual tensile stresses.

Each of these are discussed in the following subsections.

2.2.1 Initial Weld Defects

The total fatigue life of a structural component may be divided into two phases:

1. Crack Initiation; and Crack Propagation.

For plain plate and smooth lightly notched components the initiation phase is the most important with the majority of the life being spent in the initiation of small cracks. However, in the case of welded components it is generally accepted that small crack-like defects inherently exist at the welds from the welding process and therefore the initiation phase is relatively insignificant. The bulk of the fatigue life in welded components is spent in propagation of these crack-life defects until final failure occurs. For example, experimental results on joints with full penetration transverse welds have shown that about 70 % of the fatigue life is spent in propagation of weld toe cracks from an initial size of 0.5 mm (0.02 in.) to final failure, Bell et al. (1987), Vosikovsky et al. (1985) and Yee et al. (1990).

The defects which can occur at a welded joint are:

1. Slag inclusions
2. Porosity
3. Lack of penetration
4. Lack of sidewall fusion
5. Liquation cracking
6. Solidification cracking
7. Hydrogen cracking
8. Excessive undercut

The first two defect types are not often a problem though limits are placed on the length of slag inclusions. The remaining five defects are planar in character and can be serious in terms of their influence on fatigue life and brittle fracture.

Figure 2.5 illustrates various types of defects which significantly affect the fatigue life of welds. Figure 2.6 gives an indication of the relative sizes of inherent weld defects for various welding processes. Techniques that remove defects at the weld toe can appreciably extend initiation life, thus increase the overall fatigue life significantly.

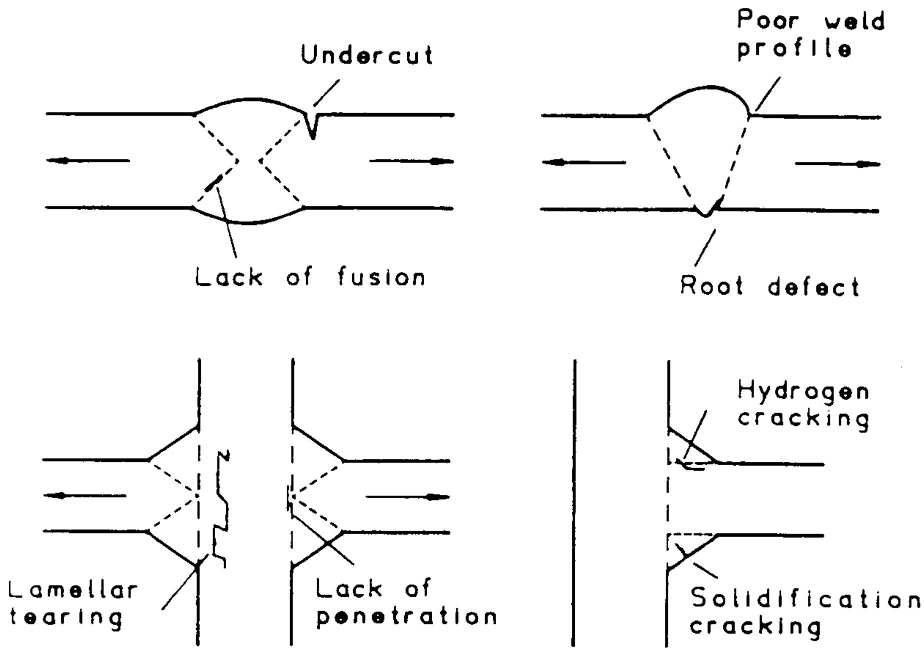


Figure 2.5 Types of Weld Defects that Significantly Affect Fatigue Life

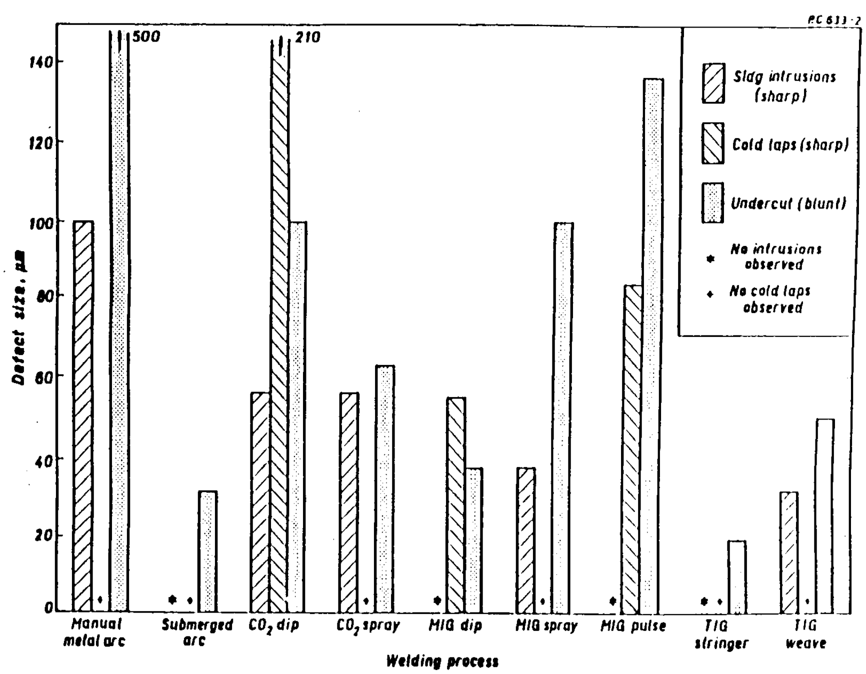


Figure 2.6 Weld Defect Sizes for Different Welding Processes (Gordon, 1993)

It should be noted that fatigue cracks originate at the weld toe in full penetration joints, but may originate at the weld toe or weld root in partial penetration welds. There is little scope for improving the fatigue strength of welded joints which fail from the root apart from ensuring, by good design, that the weld size and depth of penetration are sufficient that failure from the root is unlikely to occur.

There are potentially several sites from which a crack may initiate and grow. By toe dressing a weld, the initiation site may move to internal parts of the weld. In this circumstance, there are several weld defect types that could be an initiation site. The defects include lack of fusion, voids, porosity, cold cracks, inclusions, etc.

2.2.2 Stress Concentrations at Welded Joints

Fatigue problems tend to occur at stress concentrations in structures. Welded joints can introduce significant stress concentrations due to the discontinuities associated with the geometry of the detail and the abrupt change in section at the weld toe, and to local misalignments often present at a plate weld connection.

As illustrated in Figure 2.7, the stresses in the vicinity of a welded joint rise very rapidly and non-linearly as the weld toe is approached. The stress concentration factor due to the notch at the weld toe is a function of the weld shape and weld toe geometry which are defined by the weld toe angle, ?, and the weld toe radius, ?, as shown in Figure 2.8. Niu and Glinka (1987) proposed the following relationship for the notch stress concentration factor at a weld toe:

$$K_w = 1 + 0.5121 \cdot ?^{0.572} \cdot (t/?)^{0.469} \tag{2.1}$$

where K_w is the notch stress concentration factor due to the weld profile;
? is the weld flank angle in radians;
? is the weld toe radius;
t is the plate thickness.

Typical values of the weld toe parameters have been given by a number of researchers including Bell et al. (1989), Vosikovsky and Bell (1991) and Sablok and Hartt (1991). From these studies, weld toe radii for manual welds are in the range of 0.1 to 0.2 mm (0.004 to 0.008 in.). It should also be noted that the weld toe angle is more or less independent of weld size for manual welds (?=45° or p/4 radians is typical). Equation 2.1 predicts K_w values ranging from 1.5 to 2.3 for these values of weld toe radii and toe angles which can be considered to be representative of ship welds. Equation 2.1 also suggests that the notch stress concentration at the weld toe can be reduced by increasing the toe radius and reducing the weld toe angle, for example by profiling and / or grinding the weld.

The overall stress concentration factor of a welded detail can be considered to be the product of the notch stress concentration factor due to the local geometry of the weld profile, and the geometric stress concentration factor due to the gross geometry of the detail. The wide variation in the fatigue strength of different types or categories of welded joints, as illustrated in Figure 2.9, arises primarily as a result of variations in the severity of the geometric stress concentrations for different joint types and loading conditions. Undercuts, of the type illustrated in Figure 2.5, can also give rise to high stress concentrations. Severe geometric stress concentrations can arise in joints loaded in the transverse direction (eg., Detail 30 of Figure 2.9, Class E weld) and in short discontinuous welds loaded longitudinally (eg., Detail 36 of Figure 2.9, Class D weld), with the result that such details have relatively low fatigue strengths.

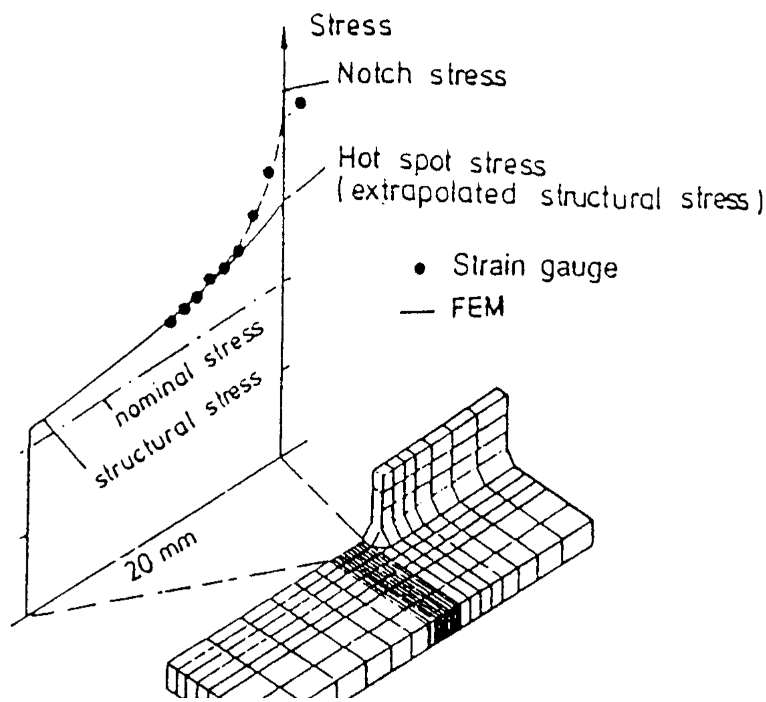
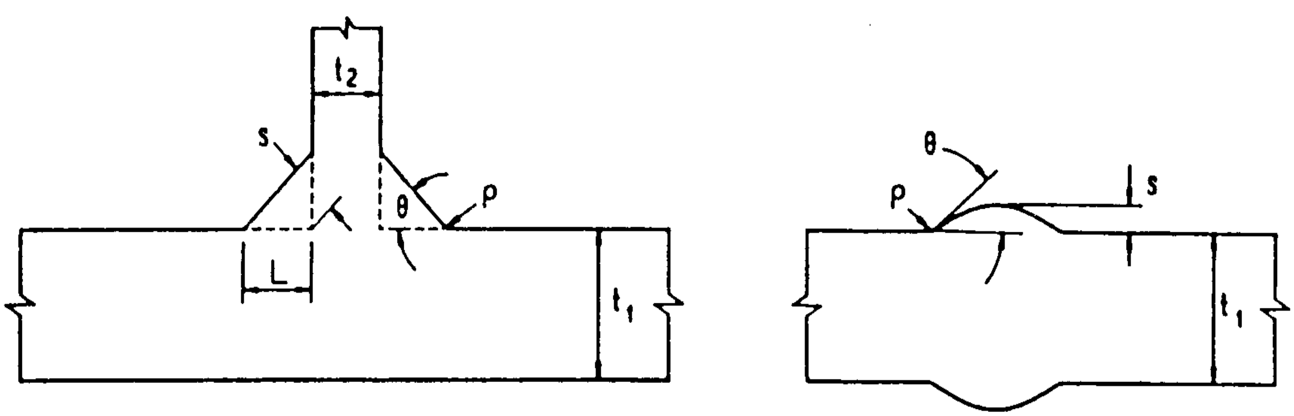
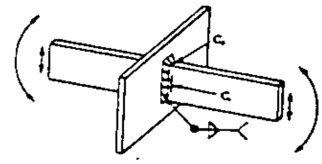
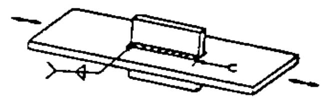
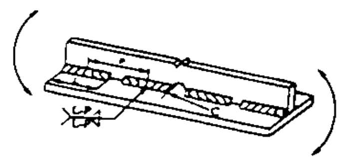


Figure 2.7 Stresses Near the Weld Toe (Maddox, 1993)

Figure 2.8 Weld Geometry Parameters (Gordon, 1993)



21	Cruciform joint, 1/4" weld, In-plane bending stress at weld toe, C		D
30	Lateral attachments to plate, Axial		E
36	Welded beam with intermittent welds and cope hole in the web, Bending		D

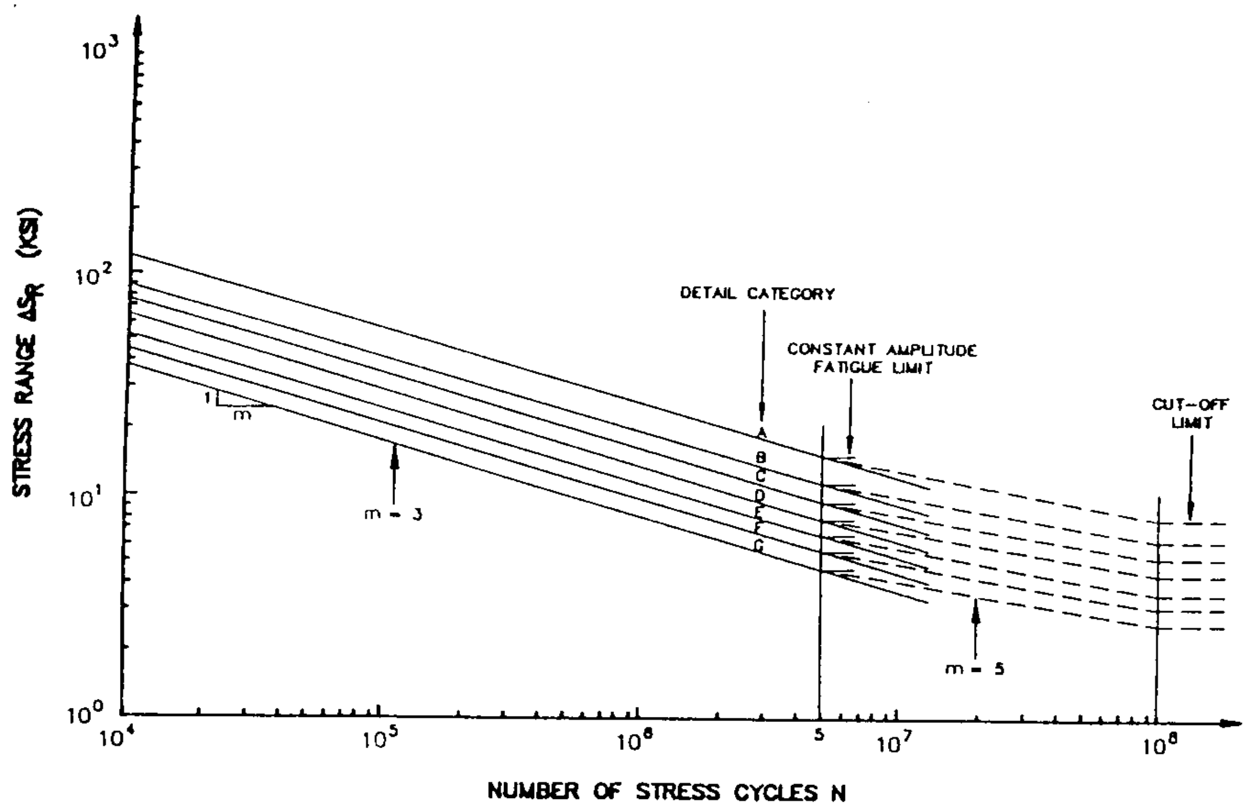


Figure 2.9 Weld Detail Fatigue Curves (Stambaugh et al., 1992; adapted from Munse et al., 1983)

It should be noted that detailed stress analysis will indicate that overall stress concentration factors for welded joints are nominally no worse than that at the edge of a hole (SCF≈3). However, Figure 2.3 shows that the fatigue strength of a welded detail is much reduced in comparison to a plate with a hole. Thus, although the stress concentration associated with a welded joint is a contributing factor, it is secondary in importance to that of pre-existing crack-like defects in terms of its effect in reducing the fatigue strength especially at long lives (high cycle / low stress regime of S-N curve).

2.2.3 Residual Stresses in Welded Joints

The welding process results in high levels of tensile residual stresses set up in and around the weld as a result of contraction of the metal after it cools down. The tensile residual stresses approach the yield strength of the base metal (Figure 2.10) and this contributes to a reduction in fatigue strength of welded components and structures. Any applied cyclic loading is superimposed on the residual stresses so that, effectively, in the vicinity of the weld the stress cycles from tensile yield stress downwards with the stress range unchanged as illustrated in Figure 2.11. Even if the loading produces nominally compressive stresses, the presence of tensile residual stresses will result in tensile cyclic stress being experienced at the weld toe. For this reason, the fatigue strength of a joint in the as-welded condition is the same in tension and compression loading as shown in Figure 2.12.

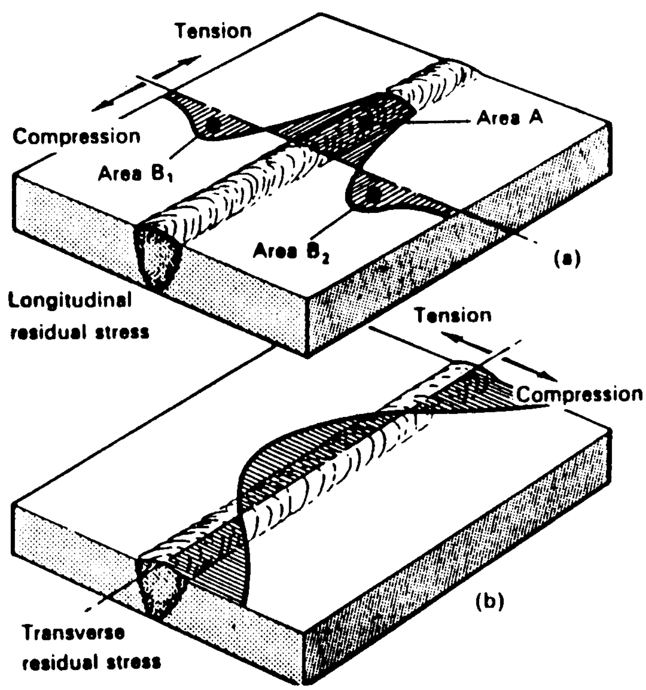
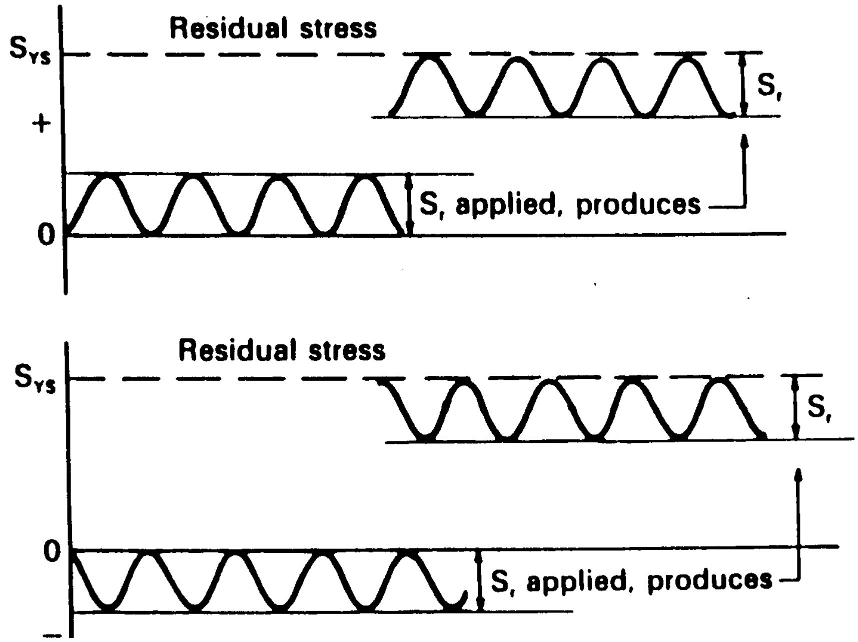


Figure 2.10 Typical Residual Stress Distribution in Welded Joint (Gordon, 1993)



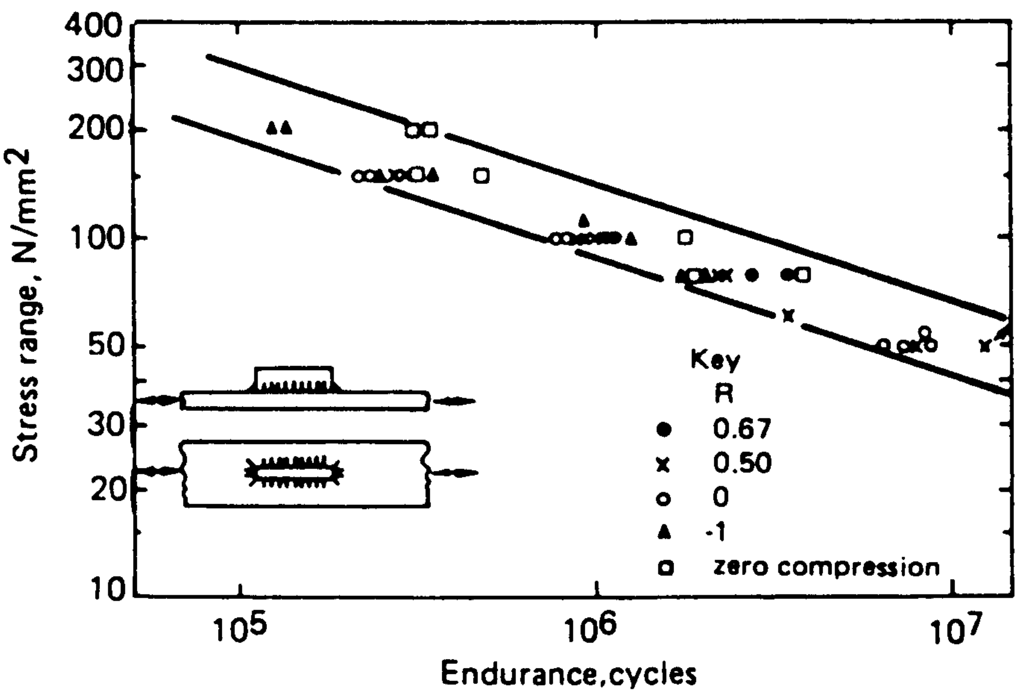


Figure 2.11 Effect Stress Resulting from Superposition of Applied and Residual Stress (Gordon, 1993)

Figure 2.12 Effect of Applied Stress Ratio on Fatigue Strength of As-Welded Steel Joints (Maddox, 1993)

In circumstances in which a joint is loaded mainly in compression, the fatigue strength can be increased by stress relief which removes residual tensile stresses at the weld, Gurney (1978). In this sense, post weld heat treatment (PWHT) or stress relief can be regarded as a fatigue improvement technique (see Section 3.5). However it should be noted that in practice local residual tensile stresses of the order of 20% to 30% of the yield strength can still remain after PWHT. In addition, in large constructions such as ship structures, there may be some longer range assembly and construction residual stresses which may also contribute a residual tensile stress field at the weld. These may be relieved to some extent with service (shake down effect), however this is difficult to predict. As a result, even when the stresses due to applied loads are nominally compressive, stress relief or PWHT may only marginally improve the fatigue strength of a welded joint in a structural assembly. Stress relief has little effect if the applied loading on the detail gives rise only to tensile stresses.

Certain techniques, such as peening treatments (see Section 3.4), effectively replace welding tensile residual stresses with local compressive residual stresses at the weld. The compressive residual stresses resulting from such treatments can approach the yield strength of the base metal. Any applied cyclic stresses will be superimposed on the local compressive residual stresses. Provided the cyclic stress range does not exceed the yield strength, the stress cycles in the vicinity of the weld remain in the compressive range. This effectively impedes crack propagation thereby increasing the fatigue strength or life of the welded joint substantially.

2.3 IMPROVING FATIGUE STRENGTH OF WELDED SHIP DETAILS

The foregoing discussion has indicated that the relatively low fatigue strength of welded joints is due to the existence of crack-like defects at the weld (hence insignificant crack initiation life), the stress concentrations associated with the weld profile and joint geometry, and the presence of tensile residual stresses arising from the welding process. The fatigue strength of welded joints in ship structures can be improved by procedures which reduce or eliminate these effects. In broad terms, this can be achieved by:

- Improvements in the design of weld details;
- Improvements in the welding and fabrication procedures; and
- Weld fatigue improvement techniques.

These are briefly discussed in the following subsections. However, before proceeding, it is worth mentioning that a fourth category may be added for improving in-service performance of welded details, namely improved inspection and maintenance procedures. This is especially important where fatigue critical details are situated in areas that can experience corrosion, such as cargo and uncoated ballast tanks, as corrosion can greatly accelerate fatigue cracking. Improved inspection and maintenance procedures that ensure the integrity and upkeep of protective coatings and anodes will also ensure that the fatigue performance of welded details in such areas are not compromised. It should also be noted that in many cases, better detail design, fabrication and / or weld fatigue improvement techniques can also result in improved application and adherence of protective coatings at welds, thereby not only improving fatigue performance, but also corrosion protection.

2.3.1 Improvements Through Better Detail Design

Designers should, in general, make every attempt to achieve the required fatigue strength from a structure by good design. The fundamental objective should be to eliminate anticipated fatigue durability problems with critical structural details (Bea, 1992), for example by ensuring proper load transfer mechanisms and minimizing stress concentrations.

Until recently, fatigue performance of details was not explicitly considered by designers. However extensive fatigue cracking experience in the Very Large Crude Carriers (VLCCs), Trans Alaska Pipeline Service tankers, and bulk carrier fleets has led to explicit fatigue design assessment requirements and procedures from each of the major Classification Societies. These rules are often accompanied by design guidance for fatigue critical details. In addition, several recent Ship Structure Committee reports (for example, SSC-374 and SSC-379) provide design guidance for selection of improved ship hull structural details relative to fatigue.

The fatigue design assessment for a detail involves evaluating the nominal stress range applied at the weld, which is primarily dependant on the geometric stress concentration factor for the detail and the manner of loading, and comparing this to the S-N curve for the category of weld. The latter S-N curves are defined for a range of basic weld categories or configurations (Figure 2.9). Figure 2.13 illustrates how the basic weld categories are related to actual ship weld details. The design guidance primarily focusses on selecting appropriate classes of weld details and reducing the geometric stress concentration factor for fatigue critical details through better proportioning and alignment of members, and improved stress continuity (eg. brackets with large radius, soft toes, tapered flanges - Figure 2.14).

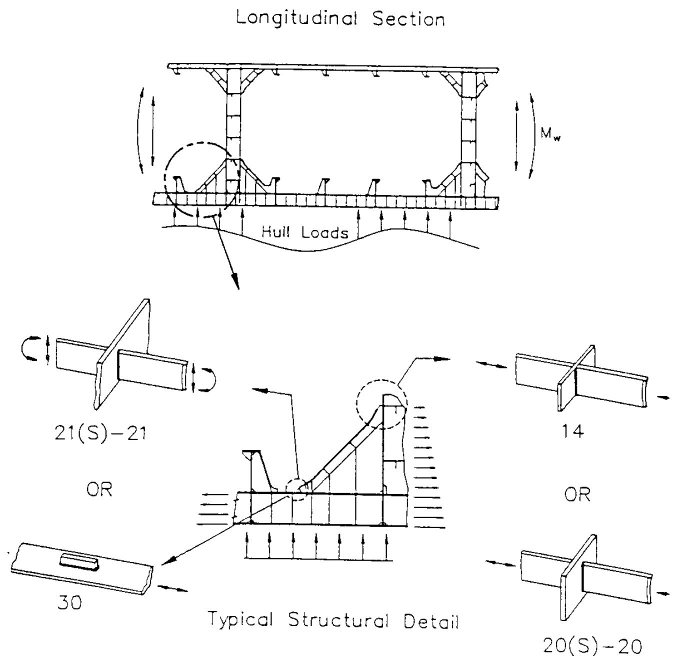


Figure 2.13 Relation Between Ship Structure Details and Basic Weld Details (Stambaugh, et al., 1992)

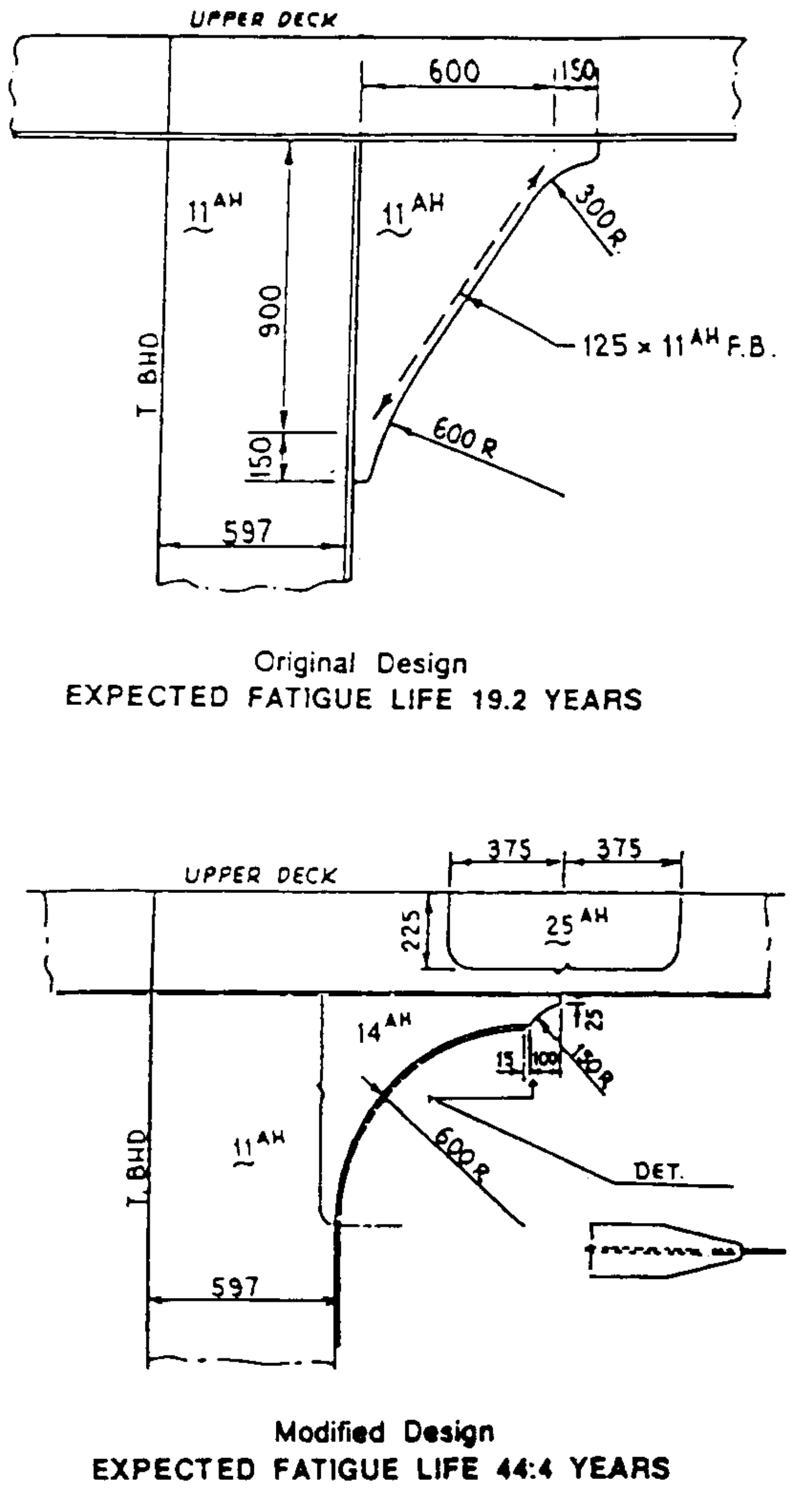


Figure 2.14 Increasing Fatigue Life by Improved Detail Design (Bea, 1992)

Note that improved fatigue strength through better detail design is essentially achieved by reducing the nominal applied stress levels and / or the geometric stress concentration factor for the welded joint. Other effects such as the presence of initial weld defects and residual tensile stresses are generally not considered.

2.3.2 Improved Welding and Fabrication Processes

There is increasing evidence to show that the fatigue life of welded joints is influenced by welding processes, welding procedures, etc. Controlled assembly and welding procedures can help to reduce tensile residual stresses, and stress concentrations due to misalignments. Weld profiling and the use of special electrodes (see Section 3.4) are weld fatigue improvement methods that can form an integral part of the welding process itself. This is obviously attractive from a production point of view.

Figure 2.6 indicates that weld initial defect sizes can differ substantially for different types of welding processes and this can have a significant effect on the fatigue life. Figure 2.15 shows that different welding processes result in different weld profiles and how, in combination with different initial defect sizes, this can dramatically affect the fatigue strength of the same basic weld detail. It has also been reported that the waviness or irregularity of the weld toe in the length direction (Figure 2.16) has a considerable influence on fatigue life (Chapetti et al., 1995; Brooke, 1988; Otegui et al., 1989). In welds with large waviness, cracks are initiated only at the crests of the waves which results in a large degree of mismatch between the cracks. This delays crack coalescence and results in longer fatigue lives. This effect is proposed as an explanation of the fact that the service lives of welds made by automatic welding processes are usually considerably shorter than the lives of manual welds (Gurney, 1979).

All of these factors have important implications for the optimization of welding and fabrication processes with the aim of extending fatigue life.

2.3.3 Weld Fatigue Improvement Techniques

Weld fatigue improvement techniques are designed to improve the fatigue strength of the weld itself. Fatigue improvement of the weld is achieved by one or more of the following basic mechanisms:

- Removal of pre-existing crack-like defects at the weld toe;
- Reduction of the notch stress concentration factor by improving the shape of the weld (increasing weld toe radius and decreasing weld toe angle); and
- Removal of harmful tensile residual stresses and / or introduction of beneficial compressive residual stresses in the weld toe region.

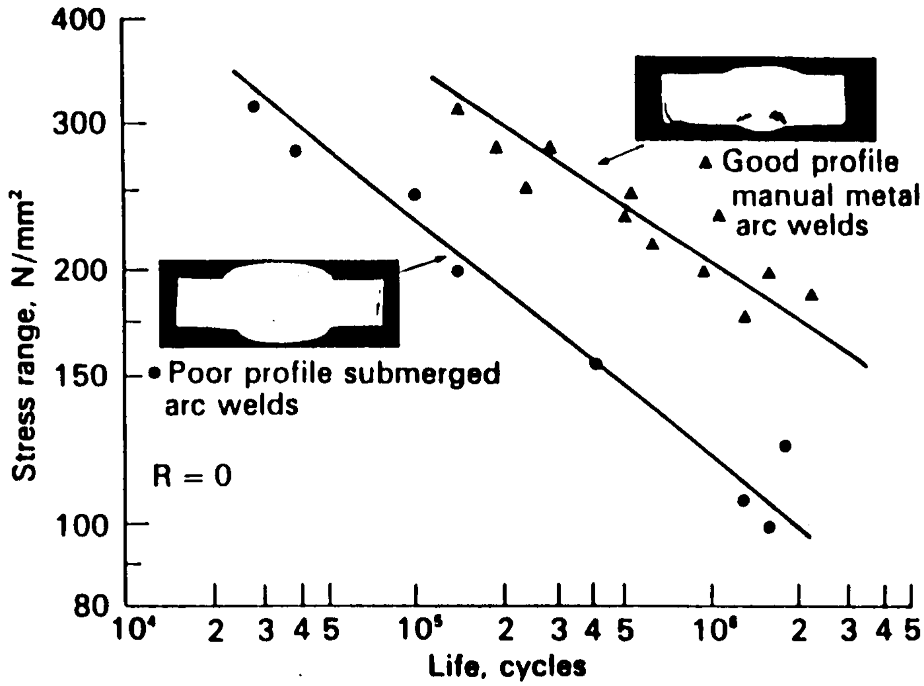
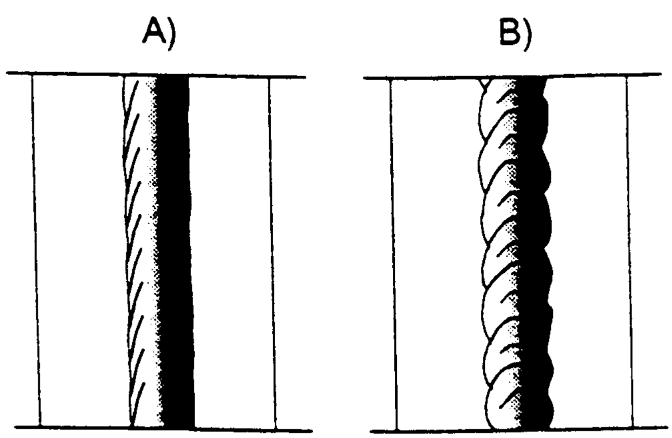


Figure 2.15 Improvements in Fatigue Strength by Different Welding Processes (Gordon, 1993)



Automatic Welding

Manual Welding

Figure 2.16 Weld Toe Irregularity for Automatic and Manual Weld Processes (Haagensen, 1996)

Such techniques can be used under circumstances where it is necessary or desirable to increase the fatigue strength of a particular weld detail, but that it is not practicable to modify the joint geometry or basic category of weld detail. Examples of circumstances in which improvement techniques might be used include (Maddox, 1983):

- To extend the fatigue life of an existing weld detail which has prematurely failed and has been repaired, if the remaining life of the structure exceeds that used before the failure occurred;

- To extend the fatigue life of an existing weld in a region which is found to be more severely loaded in service than had been assumed in design;

- Instances where the requirement is for effectively infinite life but the low fatigue limit of the welded joint is impractical; and

- Occasions when high strength material is to be utilized to increase design stresses.

The remainder of this report is devoted to the subject of weld fatigue improvement techniques. Chapter 3 presents a broad review of the complete range of techniques that are currently available to improve the fatigue strength of welded joints. Chapter 4 focusses on the practical application of three of these techniques (toe grinding, TIG dressing and hammer peening) to ship structures.

3.0 GENERAL REVIEW OF FATIGUE IMPROVEMENT TECHNIQUES

3.1 INTRODUCTION

As stated previously, the fatigue life of welded components and structures is dominated by the fatigue crack propagation phase because the initiation phase is insignificant or in some cases non-existent due to the presence of initial defects resulting from the welding process. Other factors affecting the fatigue strength of welded joints include the stress concentrations associated with the weld profile and joint geometry, and the presence of tensile residual stresses arising from the welding process. In many cases the fatigue life of welded components and structures can be substantially improved both during initial manufacture and repair by the application of weld improvement methods which reduce or eliminate these effects.

In general the weld fatigue improvement methods can be divided into two main groups comprising:

1. weld geometry modification methods that remove weld toe defects and / or reduce the stress concentration; and

2. residual stress methods that introduce a compressive stress field in the area where cracks are likely to initiate.

This chapter reviews the various weld fatigue improvement techniques that can be applied to welded components and structures. A summary of the various improvement techniques to be considered is shown in Figure 3.1.

3.2 WELD MODIFICATION TECHNIQUES

3.2.1 Burr Grinding

Weld burr grinding is carried out using a high speed pneumatic, hydraulic or electric grinder driving rotary burrs at a rotational speed of between 15,000 and 40,000 rpm. In full profile burr grinding the complete weld face is machined to remove surface defects and to blend the weld metal with the base plate. This gives the weld a favourable shape which reduces the local stress concentration. In weld toe burr grinding only the weld toe is machined to remove weld toe defects and reduce the weld toe angle which results in a decrease in the weld toe stress concentration. For both procedures it is essential that all defects and undercuts are removed from the weld toe. Therefore material is removed to a depth of at least 0.5 mm (0.02 in.) below any visible undercut, but should not exceed 2.0 mm (0.08 in.) or 5% of the plate thickness, Figure 3.2 (BS 7608, 1993). The specifications for performing weld toe burr grinding are outlined in a recent IIW Working Group document by Haagensen and Maddox (1995). The suggested position and travel of the burr grinding tool is shown in Figure 3.3.

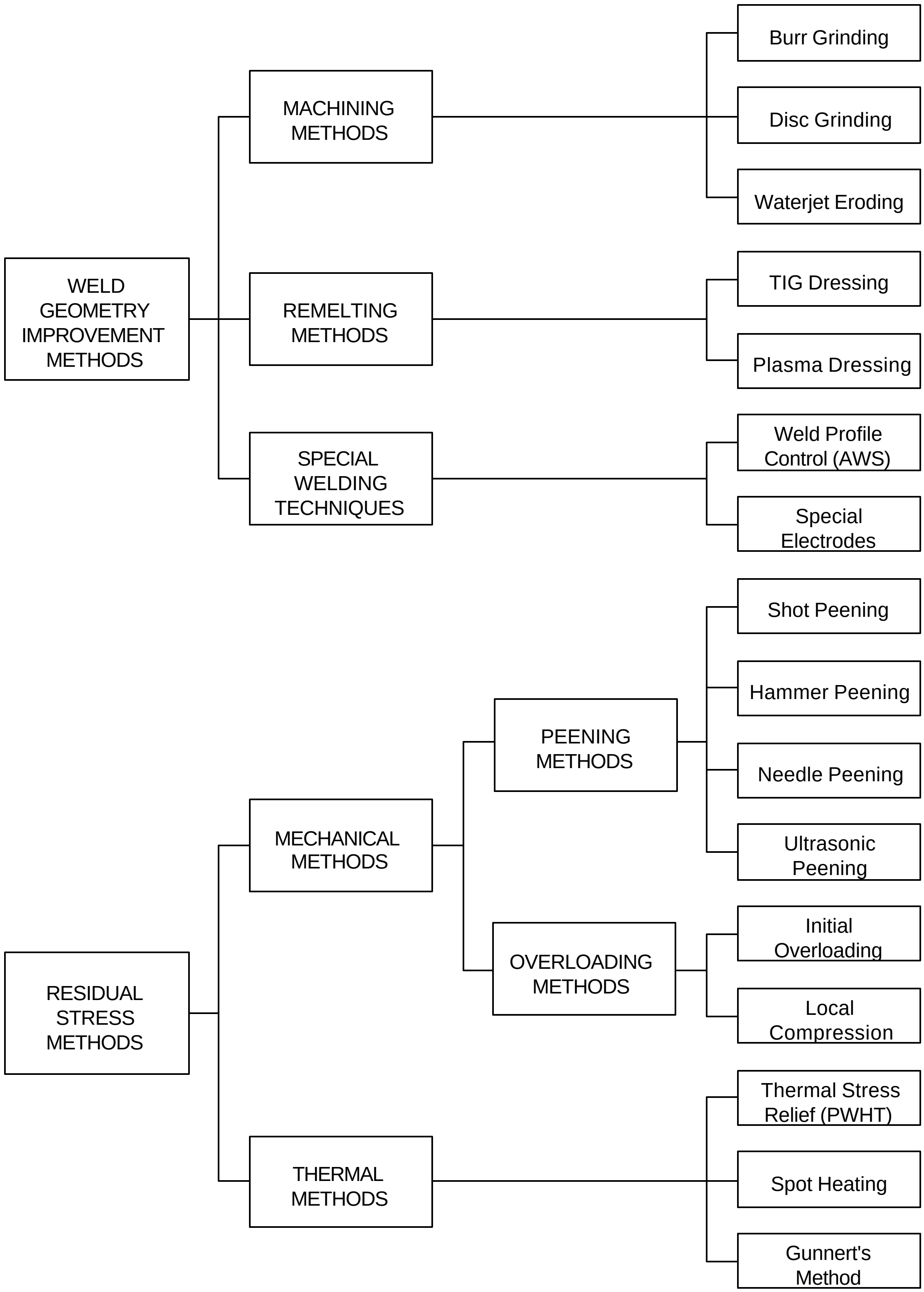
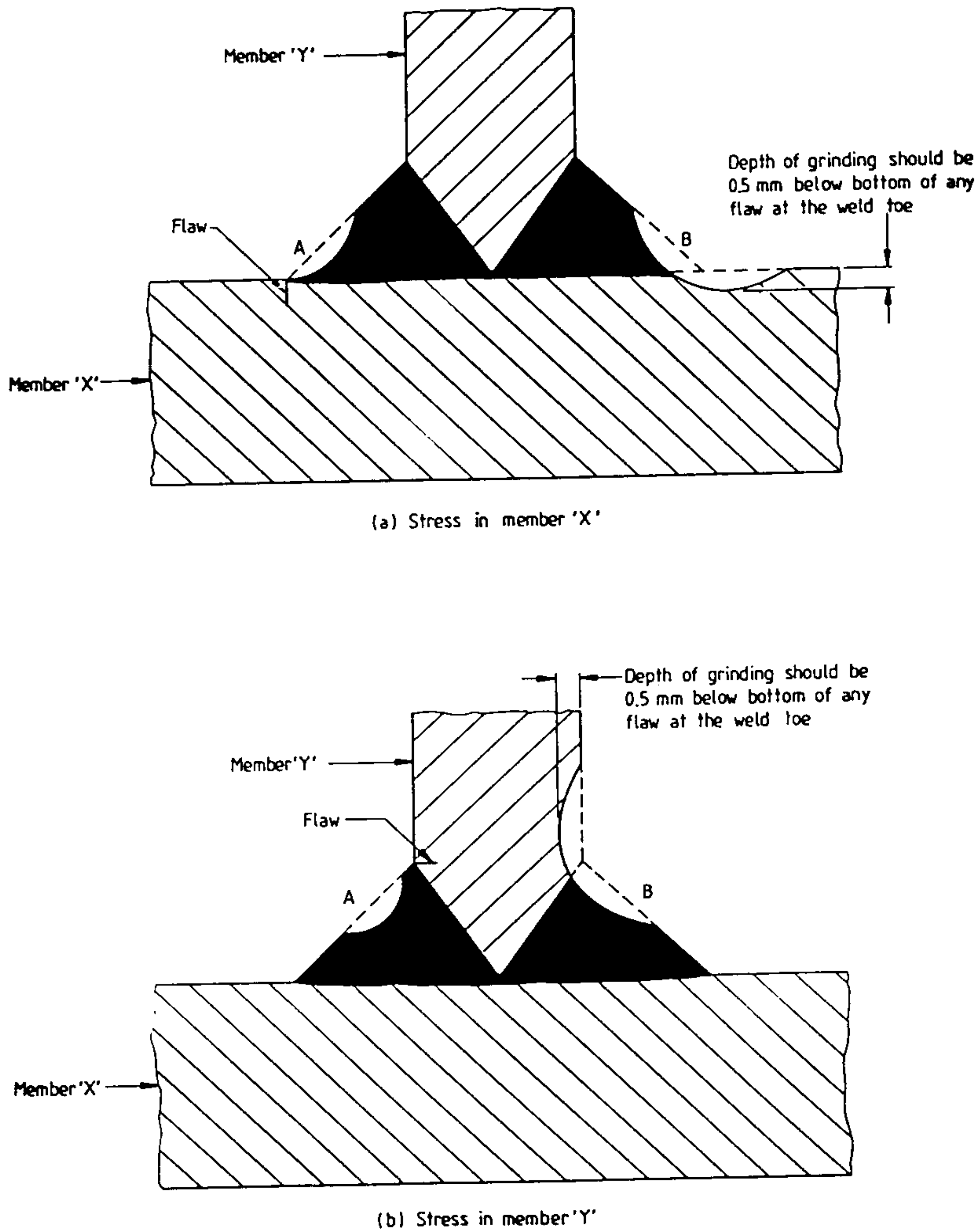


Figure 3.1 Classification of Some Weld Improvement Methods



NOTE: Grinding a weld toe tangentially to the plate surface as at A will produce little improvement in strength. Grinding should extend below the plate surface, as at B, in order to remove toe flaws.

Figure 3.2 Toe Grinding to Improve Fatigue Strength (BS 7608, 1993)

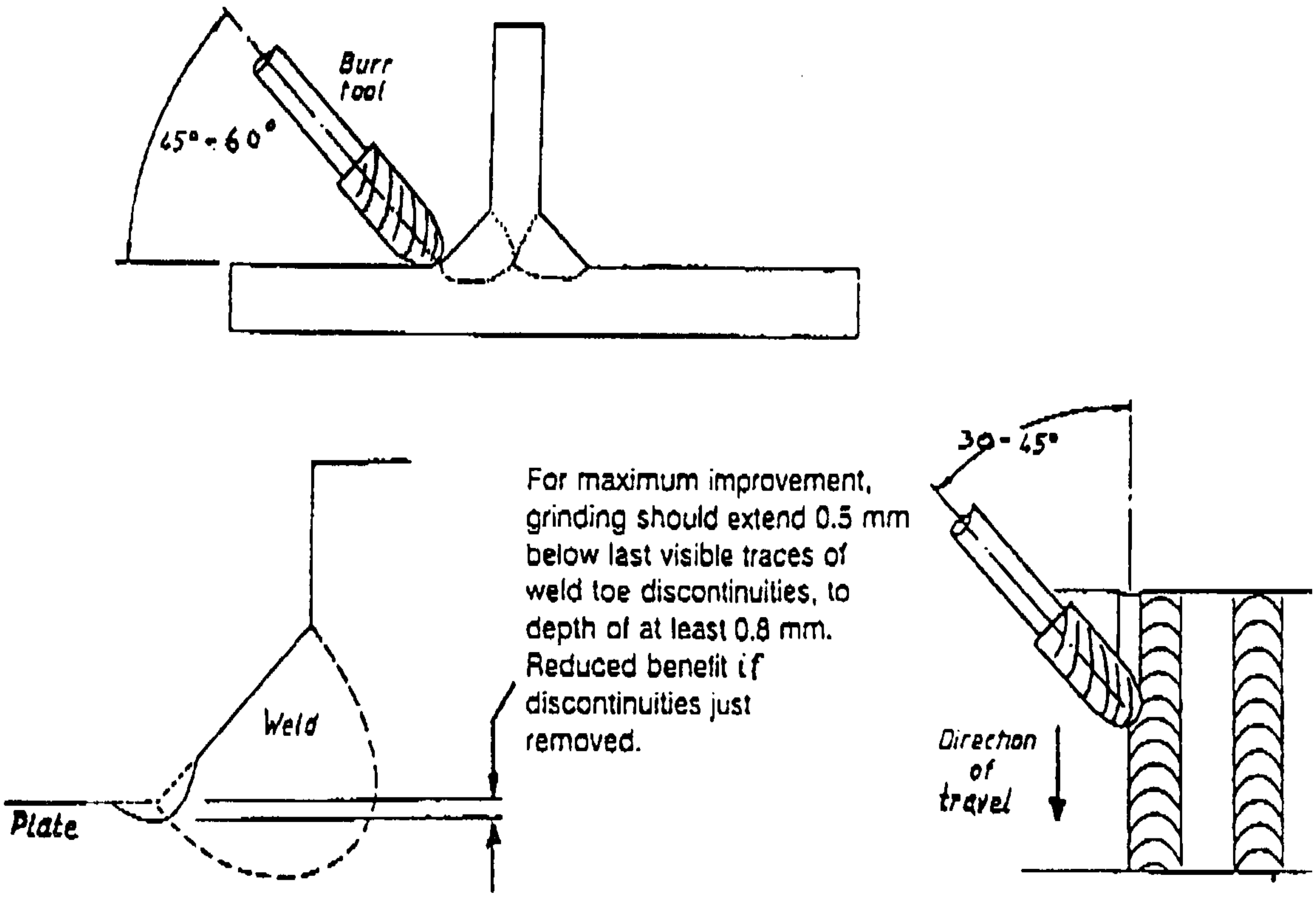


Figure 3.3 Weld Toe Burr Grinding Technique (Haagensen and Maddox, 1995)

The grinding process can be performed at the rate of about 1 metre per hour by a well equipped operator, however, the process is noisy and the operator must wear heavy protective clothing to protect against the hot sharp cuttings. The burrs have a limited life and must be changed regularly therefore the process is time consuming and expensive, Valaire (1993). Inspection of the ground welds should include the weld toe radius, and the depth of material removed at the weld toe. The improvement in fatigue strength resulting from the toe burr grinding is lower than that obtained by full profile grinding. However, the cost for toe grinding is substantially less. From the published data the range in fatigue strength improvement at 2×10^6 cycles is between 50 and 200% depending on the type of joint, Smith and Hirt (1985).

3.2.2 Disc Grinding

When a disc grinder is used to remove slag inclusions and undercuts and modify the weld shape the process is less time consuming and thus less costly, however, an inexperienced operator may remove too much material. In addition disc grinding has the disadvantage of leaving grinding marks which are normal to the stress direction in a transversely loaded weld, which serve as initiation sites for fatigue cracks. Thus the fatigue improvement results obtained using disc grinding are somewhat less than those obtained for burr grinding and the results also have a larger scatter. The fatigue strength improvement obtained for disc ground welded joints at 2×10^6 cycles is in the range of 20 to 50%, Smith and Hirt (1985).

3.2.3 Water Jet Eroding

The water jet eroding technique involves directing a jet of high pressure water which contains abrasive particles at the weld. The abrasive particles erode the weld face material removing the weld toe area including undercuts and slag inclusions. During the process the position of the nozzle is held approximately 45º to the x-axis as shown in Figure 3.4. The physical mechanisms for the resulting improvement in fatigue strength are similar to other weld toe treatments, namely, the weld toe angle is reduced to provide a smooth transition to the base plate, and weld toe inclusions and undercuts are removed resulting in a reduction in the weld toe stress concentration. It is reported, Harris (1994), that this technique can be applied more rapidly and thus more cost effectively than other toe dressing treatments such as grinding, TIG[2] or Plasma dressing. The rate of erosion is recorded as 20 to 45 m/h (65 to 150 ft/h) as compared to 0.5 to 2.5 m/h (1.5 to 8 ft/h) for grinding and 0.9 m/h (3 ft/h) for TIG dressing. However, this fast rate of erosion requires special operator training and control since there can be a risk of removing too much material in a relatively short time.

3.3 WELD TOE REMELTING TECHNIQUES

Using these techniques the weld toe region is remelted to a shallow depth which results in a weld joint with a substantially increased fatigue strength. This increase results from an improved weld toe shape with a reduced stress concentration factor, the removal of slag inclusions and weld toe undercuts and a higher hardness in the heat affected zone, Kado et al. (1975). The remelting or weld toe dressing process is carried out using Tungsten Inert Gas (TIG) or Plasma welding equipment. A major advantage of these processes is that they are both suitable for automation. However, one disadvantage is that it is difficult to establish an inspection criterion to ensure that the process has been carried out satisfactorily.

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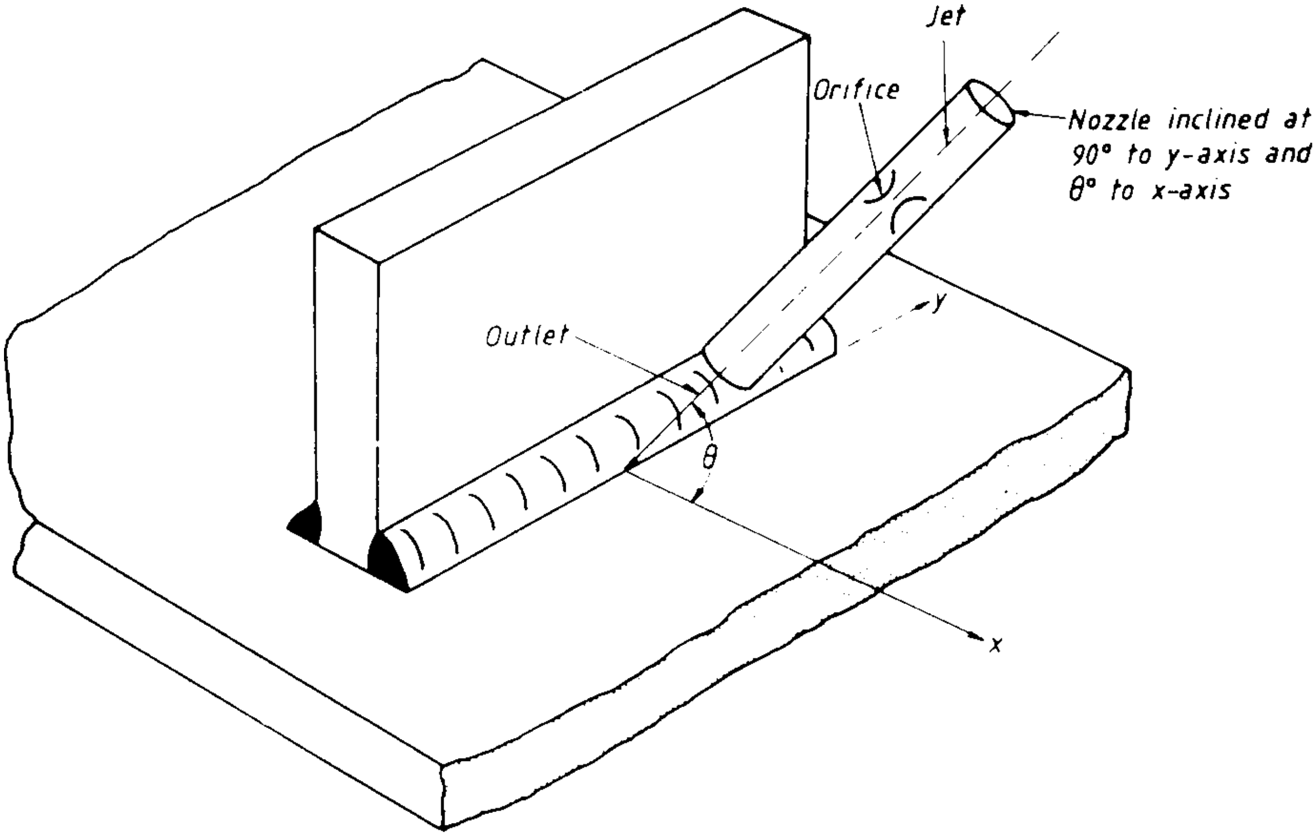
[2] TIG (Tungsten Inert Gas) Dressing has traditionally been used to describe weld toe remelting techniques using TIG welding equipment. This terminology is used throughout this report. Current terminology for the TIG welding process is GTAW (Gas Tungstem Arc Welding) as defined by the American Welding Society.



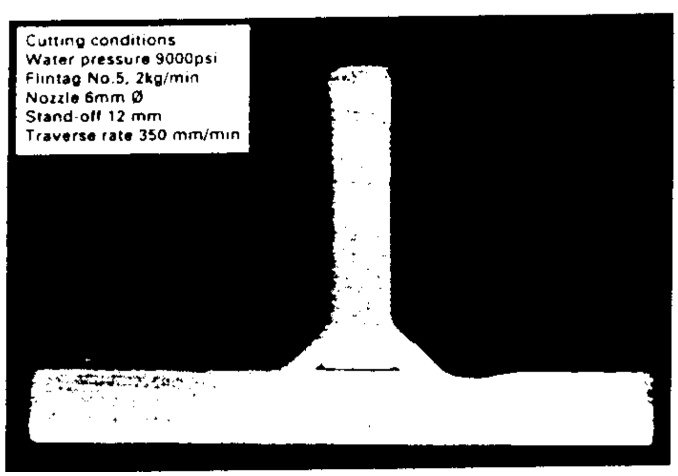


Figure 3.4 Technique for Abrasive Water Jet Toe Dressing (Harris, 1994)

3.3.1 Tungsten Inert Gas[3] (TIG) Dressing

In this technique, standard TIG welding equipment is used without the addition of any filler material, at typical heat inputs of 1.0 to 2.0 kJ/mm (25000 to 50000 J/in.). Optimum conditions for TIG dressing have been proposed by Kado et al. (1975). The depth of penetration of the arc is approximately 3 mm (0.12 in.), however, in some cases a deeper penetration of 6 mm (0.25 in.), produced by higher heat inputs, has been used to remove 4 mm (0.16 in.) deep fatigue cracks, Fisher and Dexter, (1993).

In older C-Mn steels with a relatively high carbon content the remelting process produces excessive hardness levels in the heat affected zone. To remedy this problem a second TIG run procedure was developed to temper the weld toe region and produce acceptable hardness levels of 300 HV using 10 kg load, Haagensen (1978). The position of this second TIG run is about 4 mm (0.16 in.) from the first run as shown in Figure 3.5. This second TIG run also contributes to a better transition between the weld and the base plate but the overall economy of the dressing process is adversely affected.

The success of TIG dressing is very sensitive to operator skill and requires ensuring proper operating conditions such as cleanliness of weld and plate, welding current, welding speed and gas shield flow rate for optimum results. In addition, the position and angle of the torch relative to the weld toe is critical, Figure 3.6, to obtain an optimum weld toe shape as shown in Figure 3.7. For this reason and the complexity of the optimization process it has been suggested by Haagensen (1991) that the procedure be validated through a TIG dressing procedure qualification test similar to welding procedure qualification tests.

Typical results obtained from weld joints treated by this process are shown in Figure 3.8. The increase in fatigue strength at 2×10^6 cycles is approximately 50%. The variation in fatigue strength with ultimate tensile strength does not appear to exhibit a consistent trend for TIG dressed joints based on the data shown in Figure 3.9, Haagensen (1985).

3.3.2 Plasma Dressing

Plasma dressing is similar to TIG dressing, the main difference being higher heat input of about twice that used in TIG dressing. The higher heat input produces a larger weld pool which results in a better transition between the weld material and the base plate. Also the larger weld pool makes this procedure less sensitive to electrode position relative to the weld toe.

It has been found that the improvements in fatigue life obtained from plasma dressing are generally greater than for TIG dressing particularly for higher strength steels, Figure 3.10, Haagensen (1985). The cost of TIG and Plasma dressing is relatively inexpensive, however, the heavy cumbersome equipment and accessibility may limit use.

[3] See footnote 2.

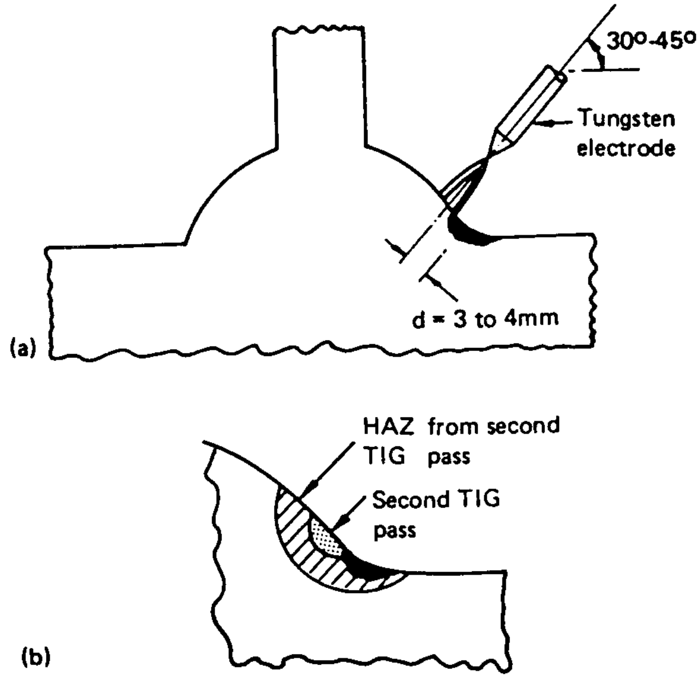
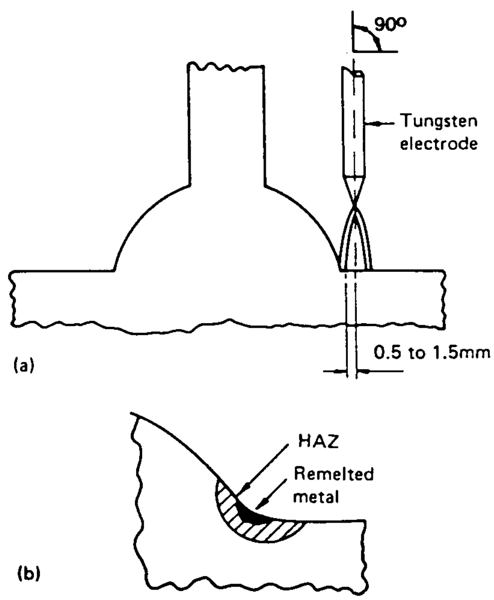
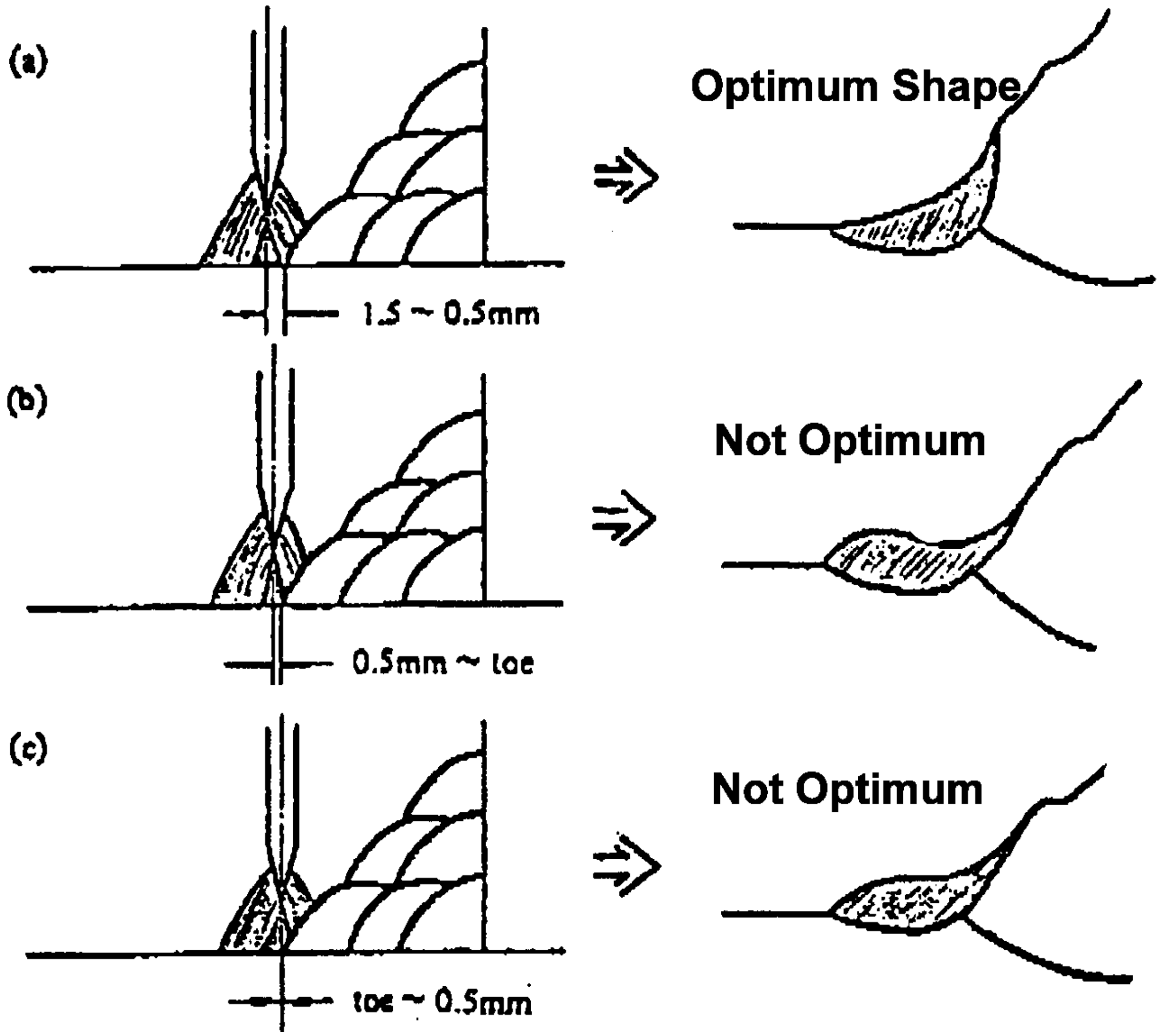


Figure 3.5 Modified TIG Dressing Technique (Haagensen, 1991)



(a) Position of Electrode (b) Bead profile

Figure 3.6 TIG Dressing (Haagensen, 1991)



(b) and (c) are too close to toe resulting in non-optimal shape

Figure 3.7 Position of TIG Electrode and the Resulting Profiles (Kado et al., 1975)

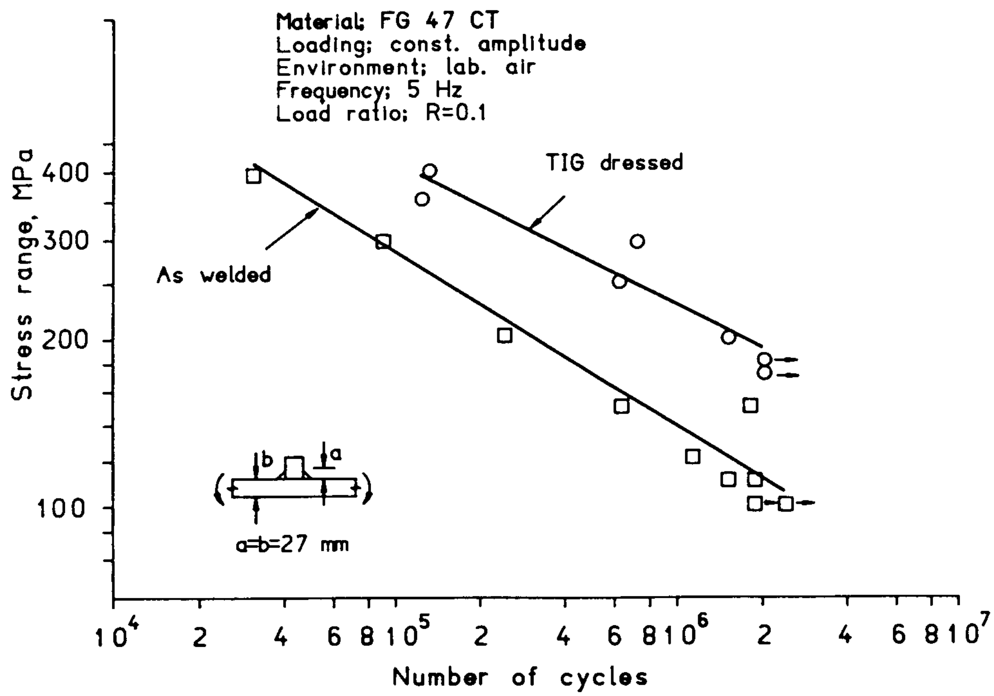


Figure 3.8 Effect of TIG Dressing on the Fatigue Strength of a Medium Strength Steel

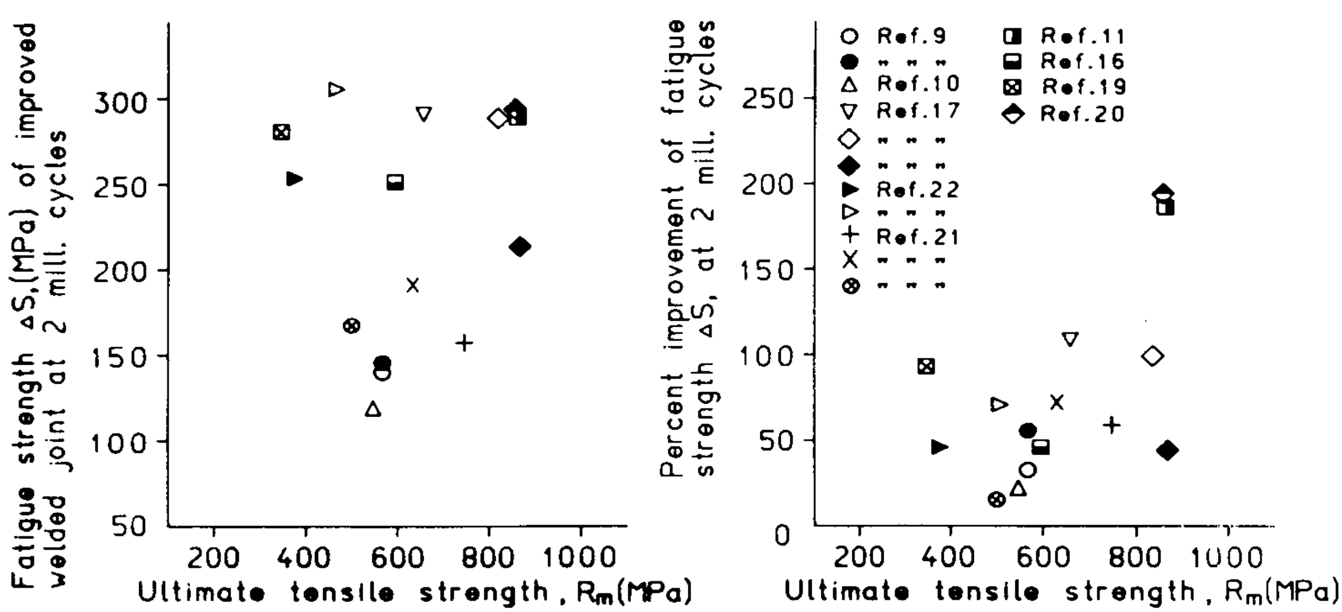


Figure 3.9 Variation in Fatigue Strength Improvement Due to TIG Dressing as a Function of Base Material Strength (Haagensen, 1985)

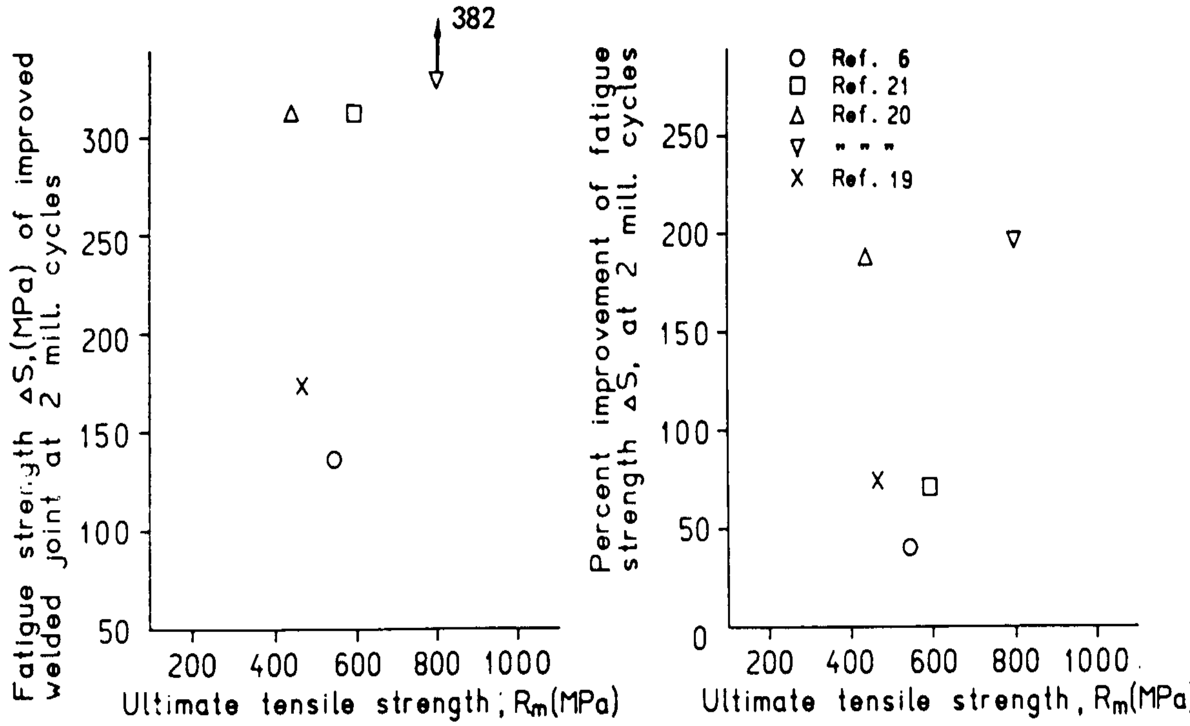


Figure 3.10 Variation in Fatigue Strength Improvement Due to Plasma Dressing as a Function of Base Material Strength (Haagensen, 1985)

3.4 SPECIAL WELDING TECHNIQUES

Special welding techniques are fatigue improvement methods that are applied as part of the welding process and attempt to eliminate costly post weld finishing. This approach is attractive because at the production stage costs are lower and quality control is simpler than for post weld procedures. The goal of these procedures is to produce improved weld shapes and thus reduce the stress concentration at the weld toe.

3.4.1 AWS Improved Profile Welds

In the AWS Structural Welding Code (1996), a reduction in the stress concentration factor in multipass welded joints of the type shown in Figure 3.11 is obtained by controlling the overall weld shape. In this procedure, a concave weld profile is specified as shown in the figure and a smooth transition at the weld toe is ensured by the use of the “dime test”. As shown in the figure, the profile radius "R" recommended is dependent on the plate thickness "t". The weld toe pass (butter pass) is laid down before the capping passes and the weld toe is inspected using a “dime” of diameter equal to the attachment thickness (to a maximum diameter of 50 mm or 2 in.). If the weld does not pass the dime test, remedial grinding at the weld toe and at inter-bead notches can be carried out. It has been shown that the fatigue strength of weld joints can be increased by weld profiling, the benefit being attributed mainly to the stress concentration being moved to a lower stress region by an increase in weld leg length, Vosikovsky and Bell (1991). Typical reductions in stress concentration factor are from 3.3 - 5.1 for as-welded joints to 1.36 - 1.56 for AWS profiled joints, Vosikovsky and Bell (1991). Haagensen et al. (1987), Figure 3.12, give results for transverse welded plates with improved welds tested in bending which show an increase in fatigue strength of 25 to 30%. The results emphasize the importance of good workmanship in providing a long leg length and a low weld toe angle.

The effect of profiling will generally reduce the throat thickness. In some cases this may be severe enough to affect the static strength of the joint. In this case there is a trade-off between static strength and fatigue strength.

In the API-RP2 guidelines for the design of tubular joints, the use of non-improved profiles are discouraged by the use of a lower S-N curve, Figure 3.13. If profile control is carried out the designer may use the X1 curve; if not, the lower X2 curve must be used. Tests on tubular joints have shown the beneficial effects of profile control, but more consistent improvements in fatigue life are obtained if the weld toe region is carefully ground as indicated in BS 7608 and described in section 3.2.1.

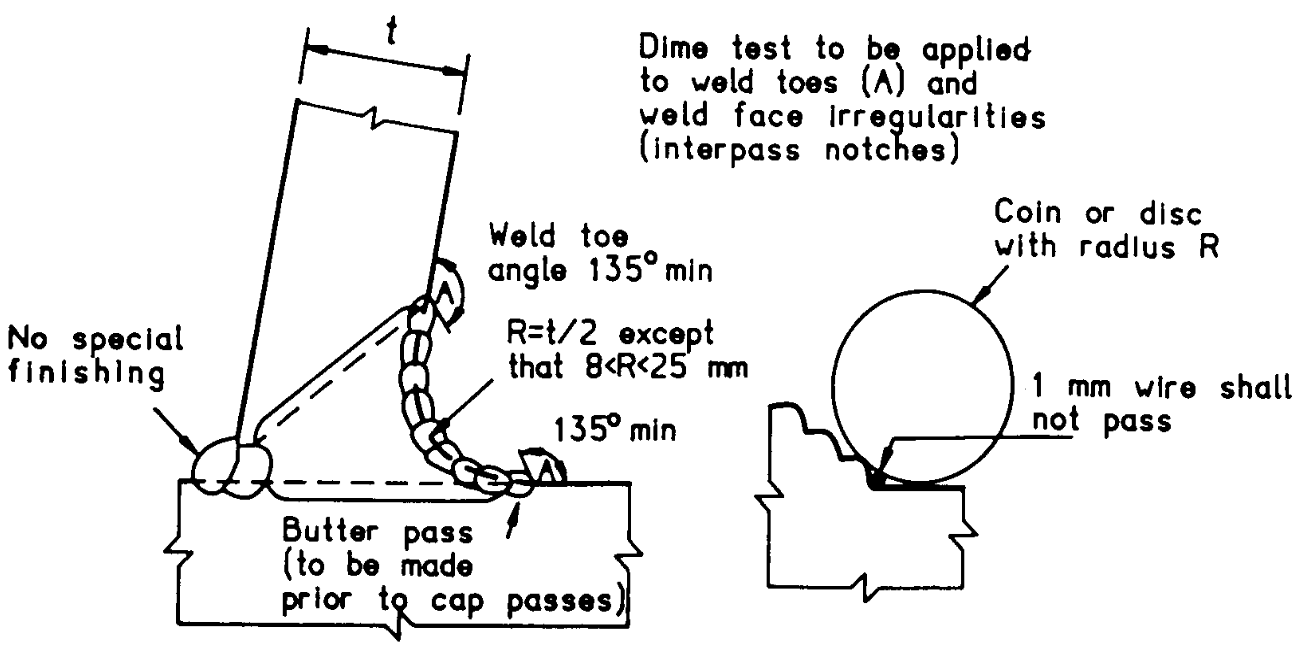


Figure 3.11 The AWS Improved Profile Weld and the "Dime Test" (AWS, 1996)

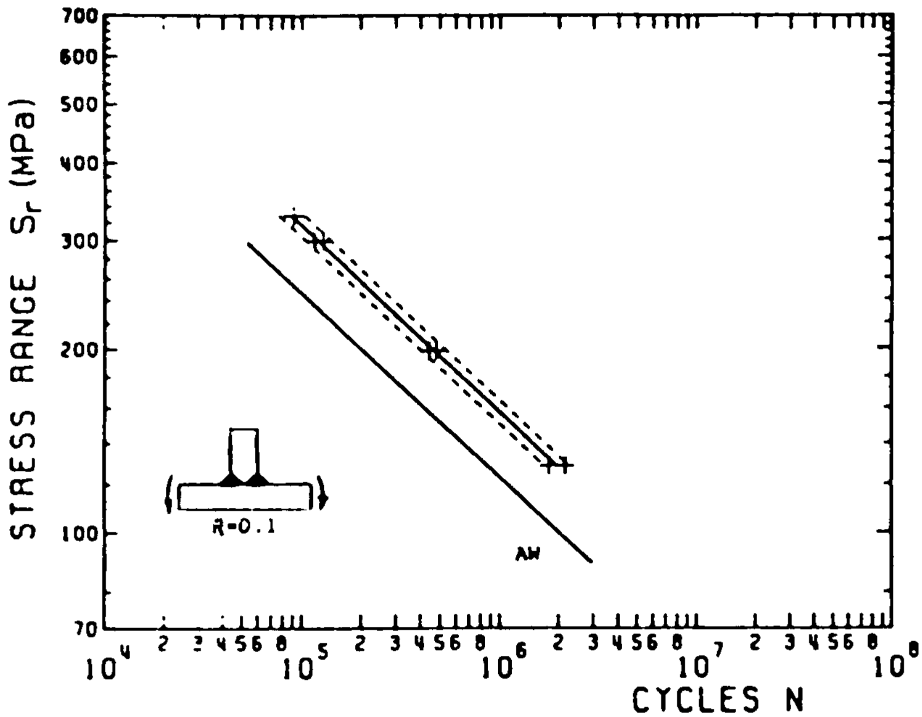


Figure 3.12 Improved Profile Weld Results for a 370 MPa Yield Strength Steel (Haagensen, 1987)

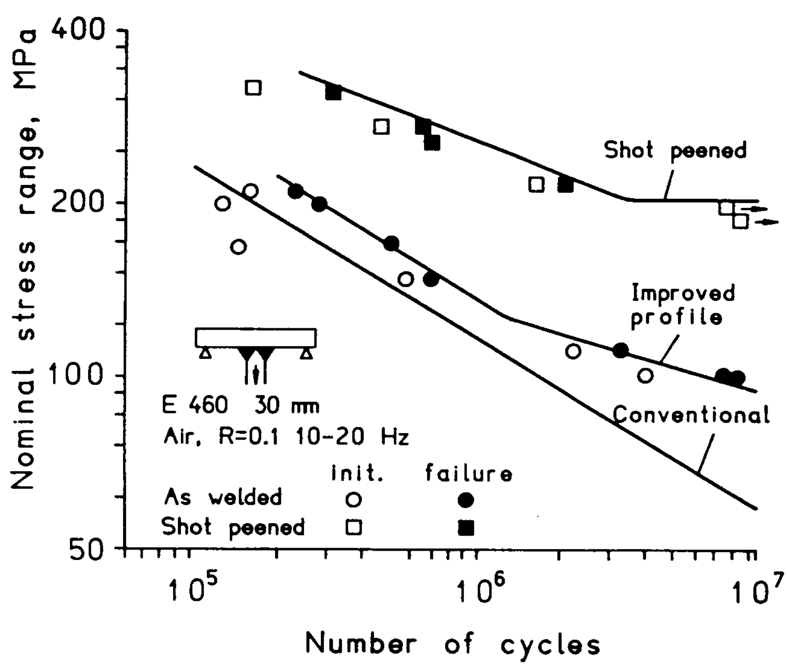


Figure 3.13 The AWS / API Design Curve (API-RP2)

3.4.2 Special Electrodes

In Japan, special manual metal arc (MMA) electrodes have been developed specifically for the final weld toe pass to give a smooth transition profile with the base plate, Ikeda et al. (1977). This is achieved because the flux gives good wetting and flow characteristics to produce a large weld toe radius which in turn results in a reduction in the stress concentration factor. The best improvements in fatigue performance using these special electrodes have been obtained with high strength steels with 500 to 800 MPa (70 to 115 ksi) strength. Bignonnet et al. (1984) reported improvement results using these electrodes which are shown in Figure 3.14. A related technique is to use special electrodes only for the finishing pass at the weld toe, Kado et al. (1975).

The improvement in weld toe parameters as a result of the use of special electrodes is shown in Figure 3.15, Kobayashi et al. (1977) and Bignonnet et al. (1987). The increase in fatigue strength as a result of the reduction in stress concentration factor in these weld specimens is shown in Figure 3.16.

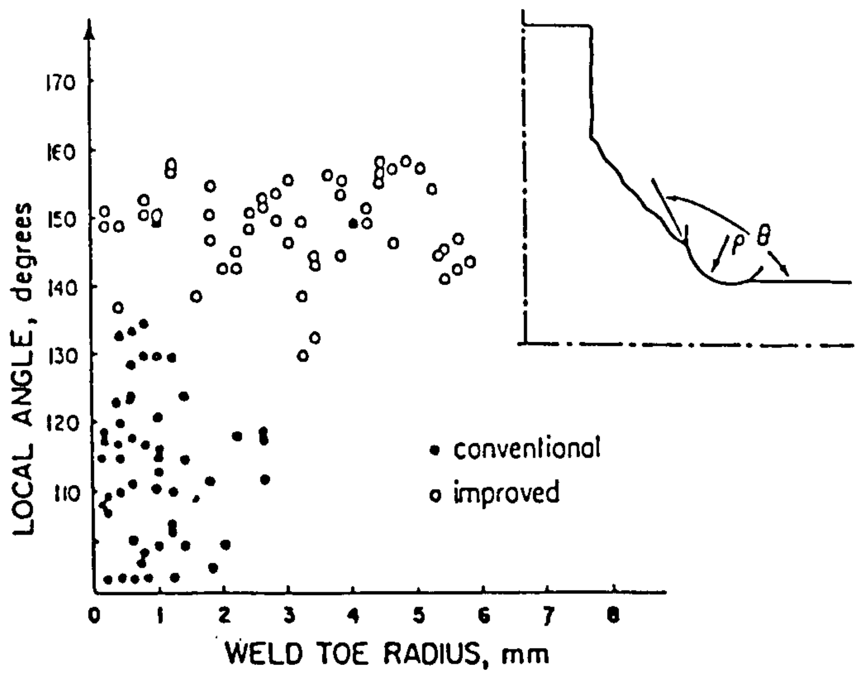


Figure 3.14 Fatigue Strength Improvements Obtained by Improved Profile and Shot Peening (Bignonnet et al., 1984)

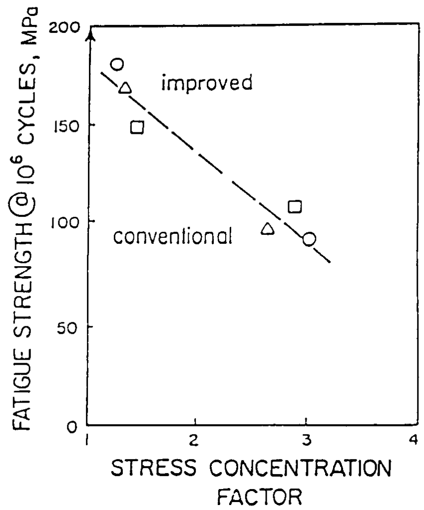


Figure 3.15 Weld Geometry Data for Specimens with Improved Weld Profiles (Kobayashi et al., 1977 and Bignonnet et al., 1987)

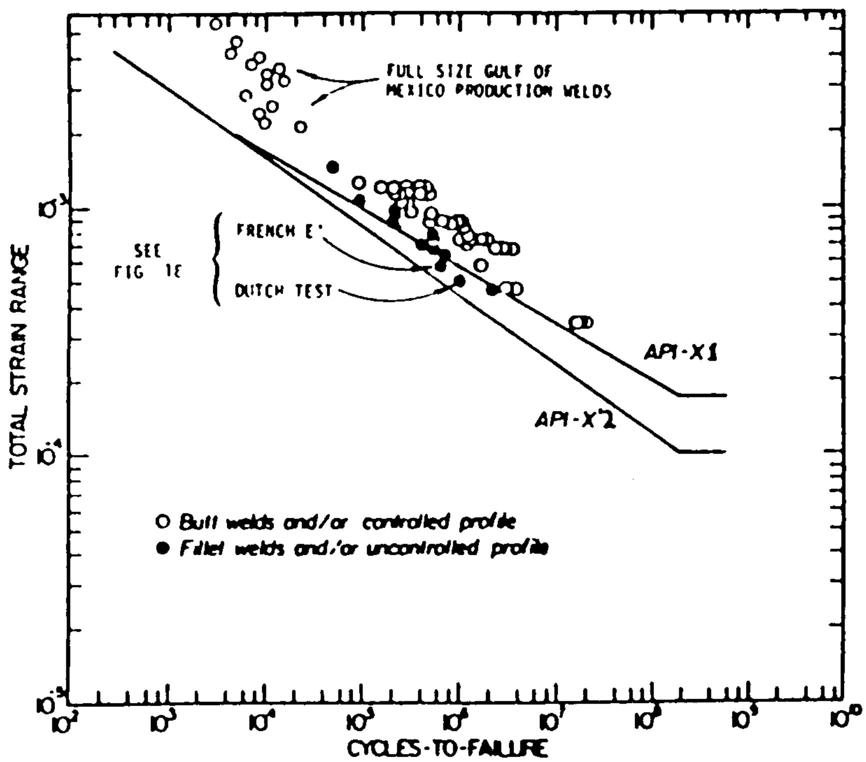


Figure 3.16 Plot of Fatigue Strength Versus Stress Concentration for Specimens with Normal Welds and Welds Prepared with an Improved Electrode (Kobayashi et al., 1977 and Bignonnet et al., 1987)

3.5 PEENING METHODS

As a result of the welding process, high tensile residual stresses exist in as-welded joints in the region of the weld. Therefore the applied stresses become wholly tensile in the weld region even if the applied stress cycles are partly compressive (see Figure 2.10). Improvement in the fatigue strength of the welded joint can be obtained if these tensile residual stresses are removed. However, a greater benefit can be realized if compressive residual stresses are introduced at the weld region.

Peening is a cold working process which plastically deforms the surface by impacting it with a tool or small metal balls. This introduces large compressive stresses of the order of the yield stress of the material. For this reason it is expected that larger improvements in fatigue strength are obtained for higher strength steels. This process effectively introduces an initiation period into the total life of the component. The heavy material deformation caused by the peening also blunts sharp inclusions at the weld toe and smooths the weld toe to base plate transition thus reducing the weld toe stress concentration factor which is an additional beneficial effect. Several methods have been developed to introduce compressive residual stresses which are briefly described below.

3.5.1 Shot Peening

Shot peening is a process similar to sand blasting with the sand replaced by small cast iron or steel shot. The shot is propelled against the surface by a high velocity air stream and causes yielding of the surface layer which builds up compressive residual stresses of about 70 to 80% of the yield stress. The effectiveness of shot peening is affected by many variables, the control of which are cumbersome and impractical, therefore only two parameters are used to specify the process. These parameters are the Almen intensity and the coverage. The intensity of the peening which is related to the depth of plastic deformation is measured by Almen strips which are attached to the surface and exposed to the same peening intensity. The Almen strips develop a curvature due to the surface deformation on the exposed side and the curvature of the strip of a given material and thickness defines the Almen intensity. The coverage is related to the area covered by the dimples produced by the shot on the surface. 100% coverage is obtained when visual examination at a 10X magnification of the surface reveals that all dimples just overlap. To produce 200% coverage the time required to produce 100% coverage is doubled.

The major advantage of shot peening is that it covers large areas at low cost, however, care must be taken to ensure that the shot size is small enough to reach the bottom of all undercuts and weld inter-pass notches. Typical shot size is in the range of 0.2 to 1.0 mm (0.008 to 0.04 in.) and the velocities of projection are in the range of 40 to 60 m/s (130 to 200 ft/s).

Results obtained from tests performed on shot peened welded joints show substantial improvements in the fatigue strength for all types of joint, with the magnitude of the improvement varying with the type of joint and the yield strength of the steel. Maddox (1982) reported an increase of 33% in the fatigue strength at $2x10^6$ cycles of joints with longitudinal attachments and fabricated from 260 and 390 MPa (36 to 56 ksi) yield strength steel while the improvement was 70% for higher strength QT steels with yield strengths of 730 and 820 MPa (105 and 120 ksi). Bignonnet et al. (1984) report typical improvements produced by shot peening as shown in Figure 3.14, however these joints were also fabricated with improved profiles using special electrodes.

3.5.2 Hammer Peening

Hammer peening is carried out manually using a pneumatic or electrical hammer operating at approximately 5000 blows / min. Hardened steel bits are used which have rounded hemispherical tips with diameters of between 6 and 18 mm (0.25 and 0.75 in.). The hammer peening tool should be held approximately normal to the weld face and inclined at 45^0 to the base plate surface as shown in Figure 3.17. The tool should be moved along the toe at a rate of about 25 mm/s (1 in/s). Knight (1978) investigated the relationship between the severity of the deformation and the effectiveness of the hammer peening and found that four passes along the weld toe produces an indentation of about 0.6 mm (0.025 in.) in mild steel and 0.5 mm (0.020 in.) in high strength steel which represents optimum treatment. He also showed that, within reasonable limits it was not possible to over-peen, reporting that after nine passes there were no deleterious effects from the peening.

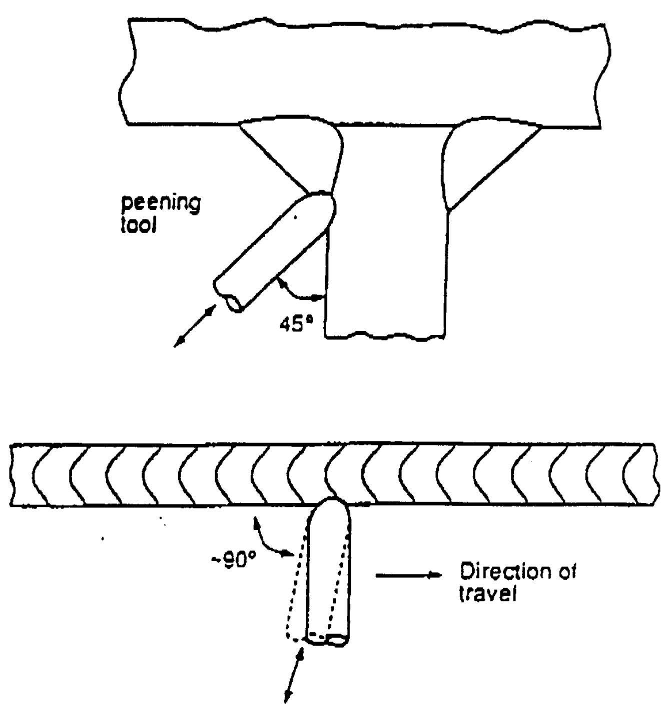


Figure 3.17 Tool Position During Hammer Peening (Haagensen and Maddox, 1995)

This type of peening produces much higher improvements in fatigue strength than either shot peening or needle peening due to the large amount of cold working produced, which results in the compressive residual stresses penetrating to a greater depth in the plate. The hammer peening treatment also reduces the stress concentration at the weld toe by modifying the weld toe angle and the weld toe radius. It has been reported in a number of cases, Gurney (1968), that the improvement produced by this treatment has been so large that the weld is no longer critical and the failure initiates in the base plate away from the weld. Results produced from a number of test programs have also shown that the largest improvements are obtained for higher strength steels, Figure 3.18, and typical improvements in fatigue strength are shown in Figure 3.19.

Hammer peening is a noisy and tedious procedure and the operator must wear protective clothing and ear protection, and these difficulties have inhibited the widespread use of this technique. New developments in modern equipment have resulted in pneumatic hammers which are lighter, vibration dampened and silenced which should result in an increase in operator comfort. This in turn should result in improved control in the peening operation giving improved consistency and reliability.

3.5.3 Needle Peening

Needle peening is a similar technique to hammer peening except that the solid tool is replaced by a bundle of steel wires of approximately 2 mm (0.08 in.) diameter with rounded ends. The improvement obtained from this treatment is generally slightly less than that obtained from single point hammer peening.

3.5.4 Ultrasonic Impact Peening

Ultrasonic impact peening is a recently developed technique to apply compressive residual stresses to weldments, Trufyakov (1993). In this process a 4 to 7 mm (0.16 to 0.28 in.) wide zone at the weld toe is treated with an ultrasonic hammer. The equipment consists of a magneto constriction transducer, an ultrasonic wave transmitter and a peening tool. The tool is either a single ball element with a 16 mm (0.625 in.) diameter or multiple needles which vibrate at 27 kHz. The process is completed in a single pass by moving the tool along the weld toe at a rate of 0.5 m/s (1.6 ft/s). The tool holder isolates the operator from the vibration and there is little audible noise during the application. The mechanism by which the improvement occurs is the same as for hammer peening. The area along the weld toe is deformed to a depth of about 0.5 to 0.7 mm (0.020 to 0.028 in.) so as to induce compressive residual stresses which introduce a substantial initiation period into the fatigue life. In addition the abrupt transition and weld undercuts at the weld toe are smoothed out resulting in a reduction in the weld toe stress concentration factor.

Trufyakov et al. (1993), have reported that improvements in fatigue strength produced by this technique for butt and overlap joints are in the order of 50 to 200%, as shown in Figure 3.20.

These authors also report that this technique has been used in the shipbuilding industry of the Confederation of Independent States (the former USSR). Other researchers, Castellucci et al. (1991), have reported similar results for transverse fillet welded joints fabricated from high strength steel.

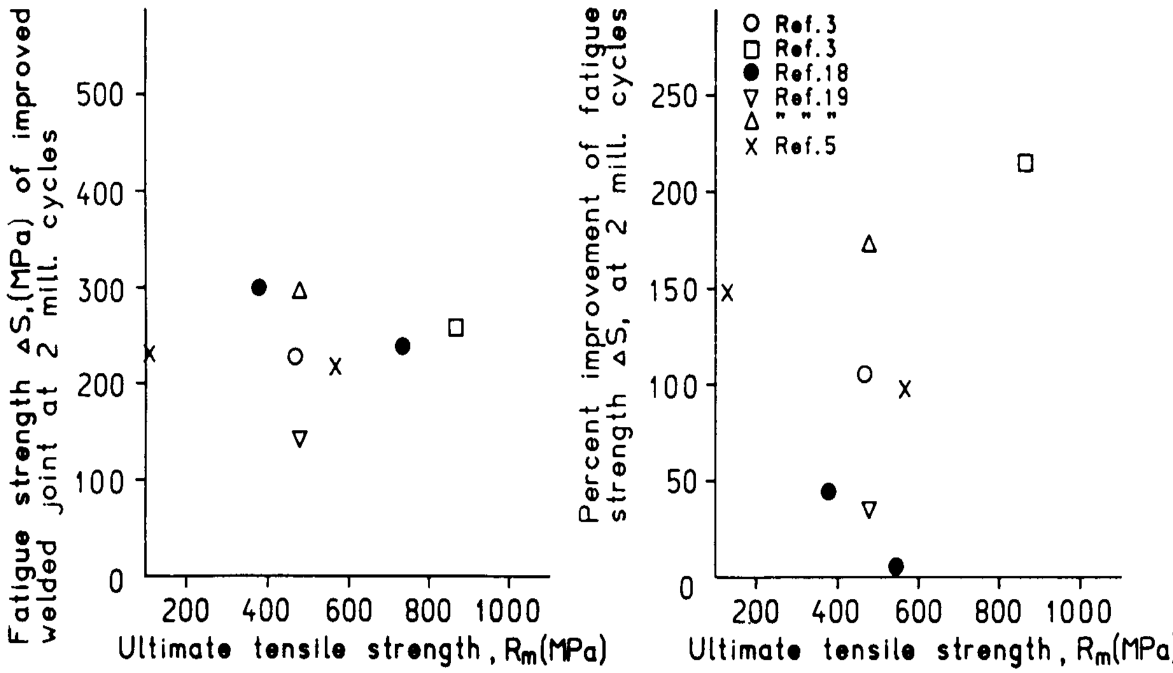


Figure 3.18 Variation in Fatigue Strength Improvement Due to Hammer Peening as a Function as a Base Material Strength (Haagensen, 1985)

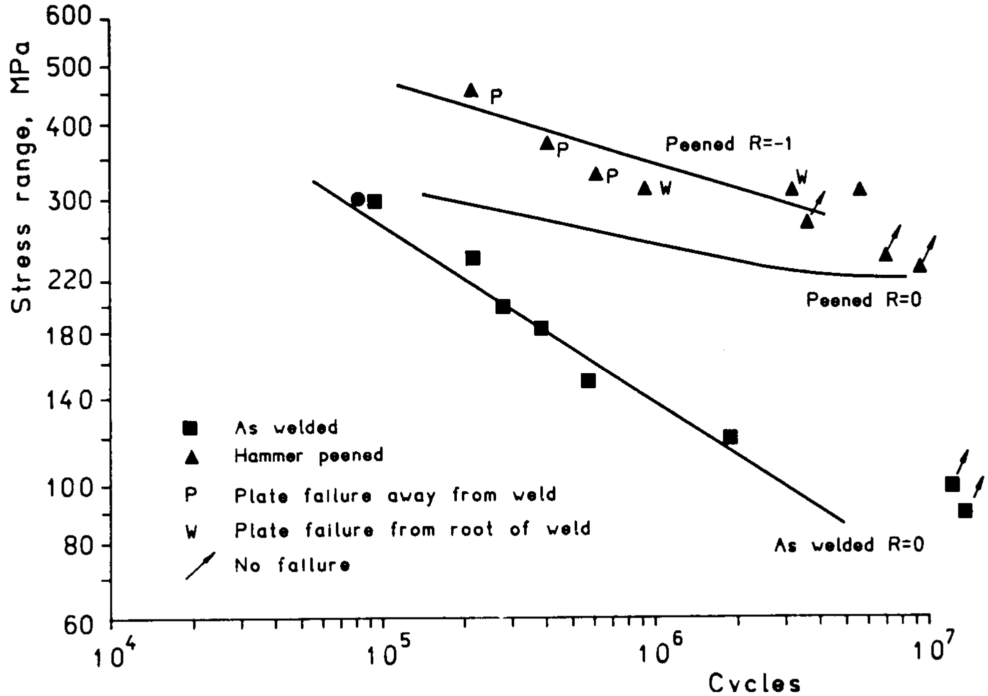
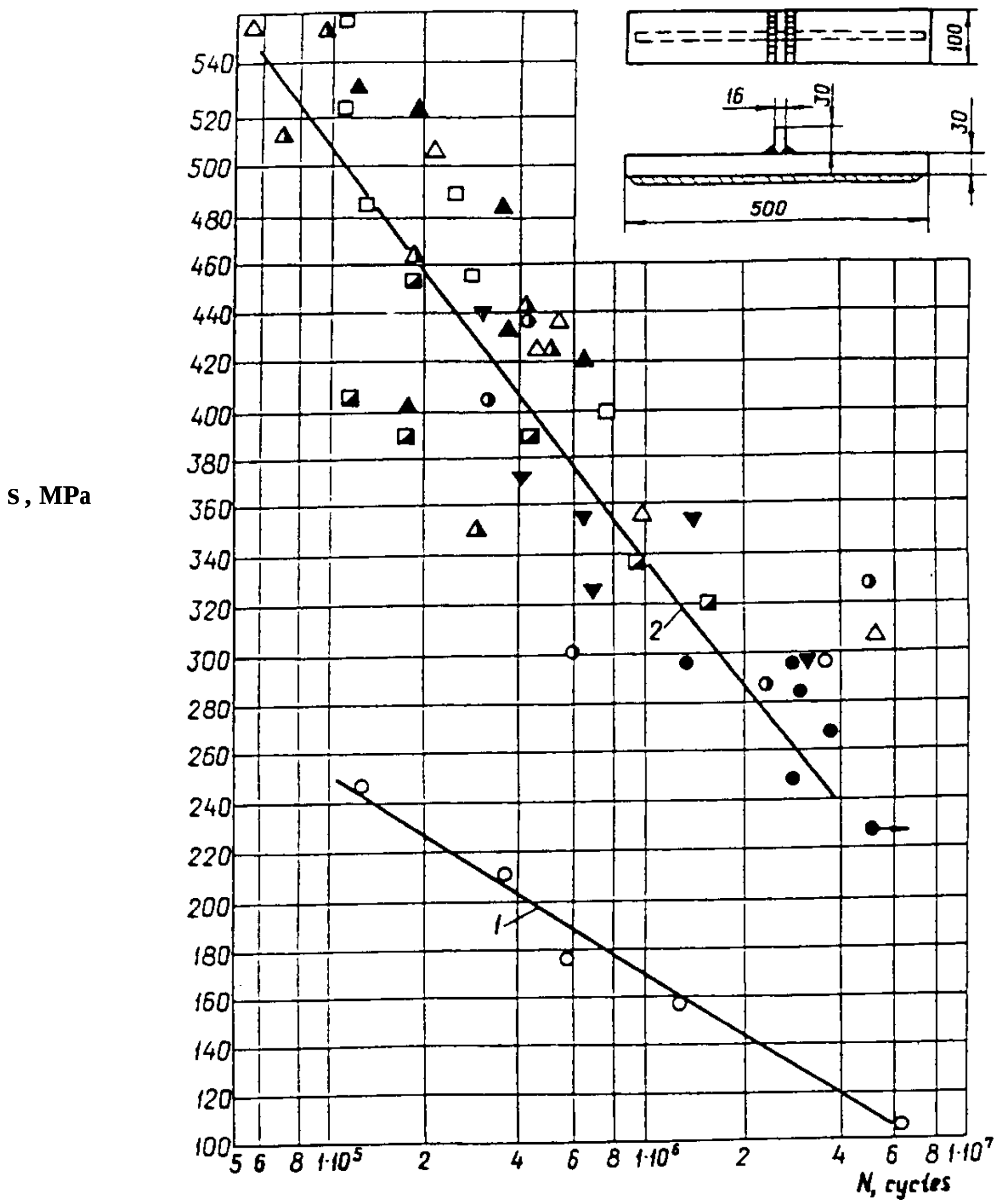


Figure 3.19 Improvement in Fatigue Strength Due to Hammer Peening (Booth, 1977)



1) As Welded **2) After Ultrasonic Impact Treatment**

Figure 3.20 Improvement in Fatigue Strength Due to Ultrasonic Impact Peening (Trufyakob et al., 1993)

3.6 STRESS RELIEF METHODS

3.6.1 Thermal Stress Relief

Post weld heat treatment (PWHT) provides a method of improving fatigue strength when the applied stresses are partly compressive. It depends on the removal of welding residual stresses from the welded joint and to some degree tempers the microstructure possibly increasing the material toughness. A typical post weld heat treatment for an offshore quality steel (50D grade) would be to heat the joint to 600ºC (1100ºF) and soak at this temperature for 1 hour per 25 mm (1 in.) of thickness and then allow to cool slowly in still air. Unlike peening techniques, PWHT does not introduce compressive residual stresses but relies on the removal of tensile residual stresses so that the applied compressive stresses may be experienced at the weld toe.

The degree of fatigue strength improvement appears to depend on the efficiency of the stress relief treatment and the proportion of the applied stress cycle which is compressive. It should be noted that after PWHT residual stresses up to 30% of yield may still be present. In view of this uncertainty and an insufficient amount of test data, design rules have not been formulated for stress relieved joints and therefore designers should assume that stress relief has no beneficial effect.

3.6.2 Vibratory Stress Relief

Vibratory stress relief is a process whereby residual stresses are relieved by vibrating the component at frequencies often close to the resonant frequency, Gnirss (1988). The success of this technique has not been proven for welded structures and it has been pointed out by Booth (1991) that vibratory stress relief techniques may use up a considerable portion of the fatigue life of the structure themselves.

3.6.3 Spot Heating

Fatigue improvement by spot heating involves the local heating of a structure, usually by an oxyacetylene torch to produce local yielding. Residual stresses are thus formed by a similar mechanism which produce residual stresses during the welding process. This local area becomes an area of residual tensile stress and because the internal stress distribution must be self-balancing, compressive residual stresses will exist some distance from the heated spot. The residual stresses produced by spot heating are shown qualitatively in Figure 3.21. The radial stresses are wholly tensile and some distance from the centre of the spot the tangential residual stresses are compressive. In order that the compressive residual stresses can be employed as a fatigue improvement technique the treated area must be located so that the line connecting the heated spot to the centre of the notch (in this case the weld toe) is at right angles to the applied stresses. Thus the expected path of fatigue crack growth would pass through the centre of the spot. The position for spot heating components with longitudinal welds is shown in Figure 3.22.

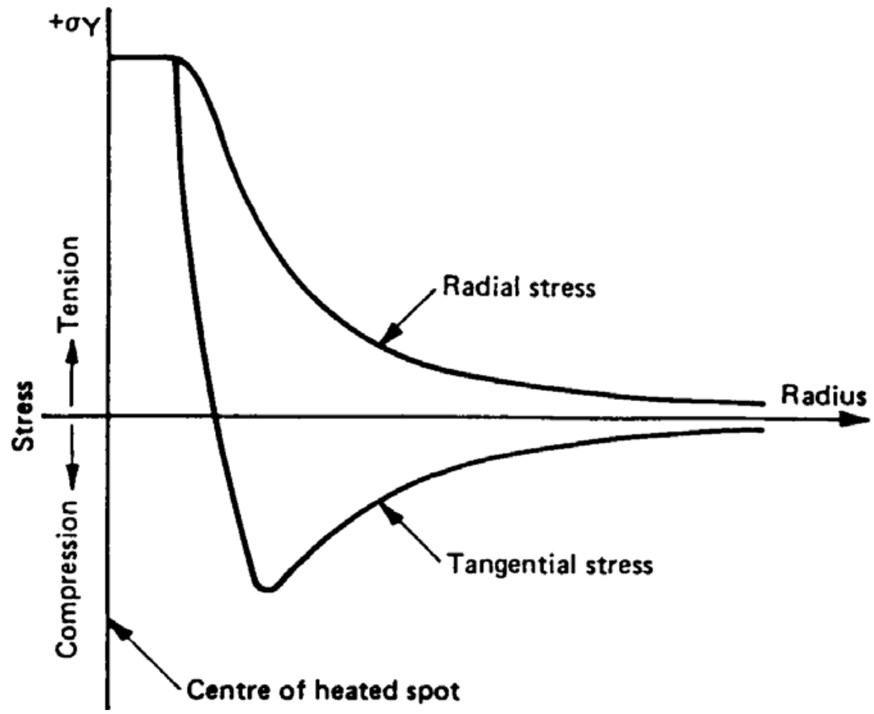


Figure 3.21 Qualitative Residual Stress Distribution Caused by Spot Heating (Booth, 1991)

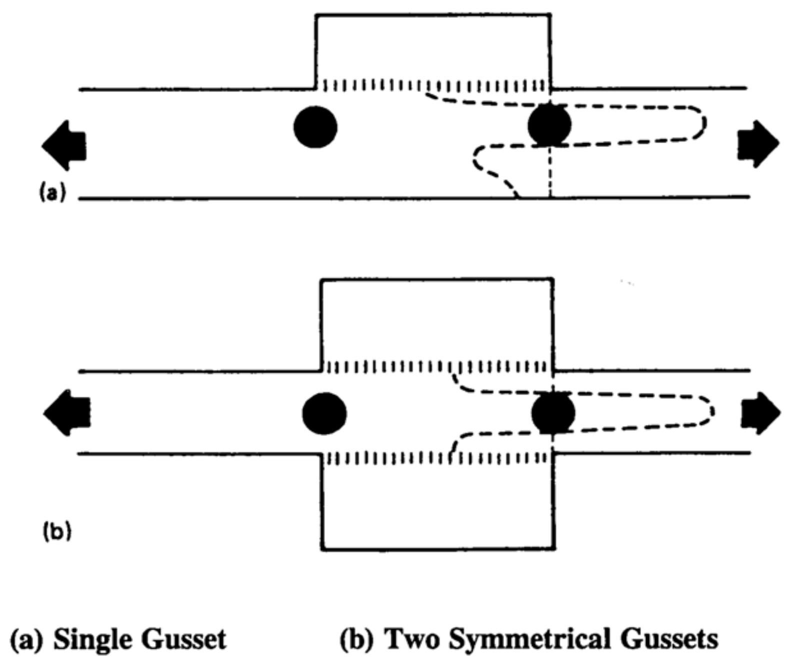


Figure 3.22 Suggested Positions for Heated Spot in Specimens with Discontinuous Longitudinal Welds (Booth, 1991)

The definition of optimum parameters for the application of spot heating requires experimental trials, however Booth (1991) has indicated a procedure for treating steel components. The size of the heated spot is about 50 to 60 mm (2.0 to 2.375 in.) as defined by the diameter of the purple, 280ºC (535ºF), temper ring. The heating time for a 12.7 mm (0.5 in.) thick plate, heated from both sides with an oxyacetylene torch, is about 10 seconds, but thicker plates would require a longer time. The spot was positioned by placing the torch so that the weld toe was about 13 mm (0.5 in.) outside the purple temper colour ring. It was reported that this procedure and position of the spot produced good results. Typical fatigue strength improvement result produced by spot heating are shown in Figure 3.23.

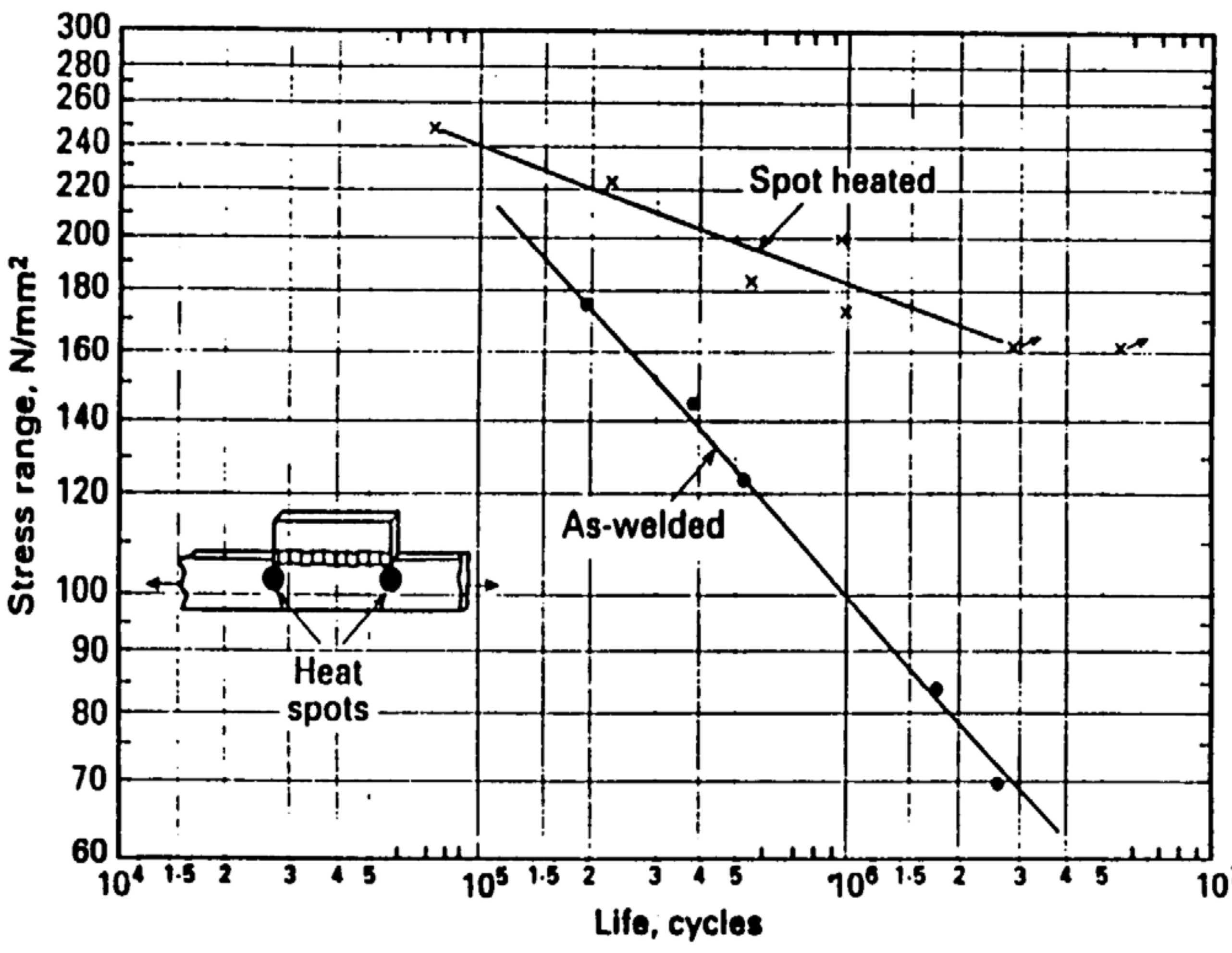


Figure 3.23 Effect of Spot Heating on Fatigue Strength of Plate with Edge Attachment (Gordon, 1993)

3.6.4 Gunnert's Method

Gunnert's method, as a technique of fatigue life improvement also involves local heating but eliminates the need for exact positioning of the spot. In this procedure the actual weld toe is heated to a temperature sufficient to cause plastic deformation and the surface is rapidly quenched by spraying with a jet of water. Thus the surface cools almost instantaneously while the underlying layers cool more slowly. As the underlying layers contract compressive residual stresses are induced in the previously cooled surface layer. The initial temperature suggested by Booth (1991) is 550ºC (1020ºF) and heating must be carried out at a slower rate than for spot heating to allow for a significant temperature gradient through the underlying layers of material. As was the case with spot heating this technique can only be carried out on components in which the area to be treated is localized.

3.6.5 Explosive Treatment

Explosive treatment is a technology suggested by researchers at the E.O. Paton Electric Welding Institute, Ukraine for relieving residual stresses, Petrushkov (1993). In this case the working tool is explosive charges of certain shapes and masses which are placed on the surface of the weldment to be treated as shown in Figure 3.24. This method is based on the premise that external loading of this nature will produce a stress state in the weld metal that is opposite to that produced by the welding process. It is claimed that explosive treatment is between 5 and 50 times more productive and cheaper than heat treatment, it does not require specialized equipment nor highly skilled personnel and gives high reproducibility of results. In the case of welds subjected to fatigue loading, this treatment relieves the tensile residual stresses in the area of the weld and replaces them with stresses of the opposite sign in the surface layers thus effectively introducing a crack initiation period into the life of the component. The improvement in fatigue life of specimens with transverse stiffeners fabricated from low-carbon steel tested with stress ratios of $R = 0$ and -1 are shown in Figure 3.25.

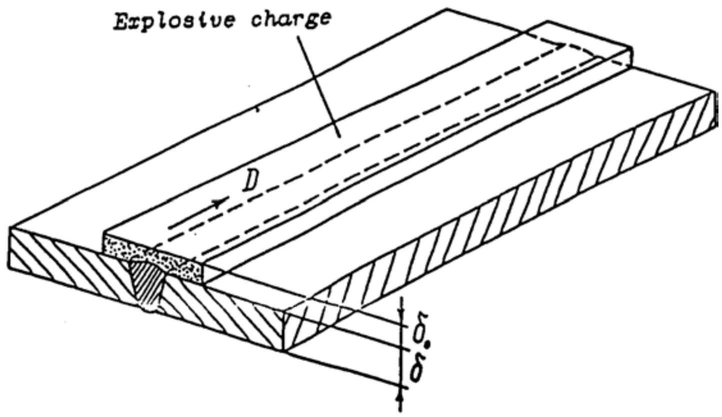


Figure 3.24 Explosive Treatment of a Butt Welded Plate Joint Using a Strip-Shaped Charge (Petushkov, 1993)

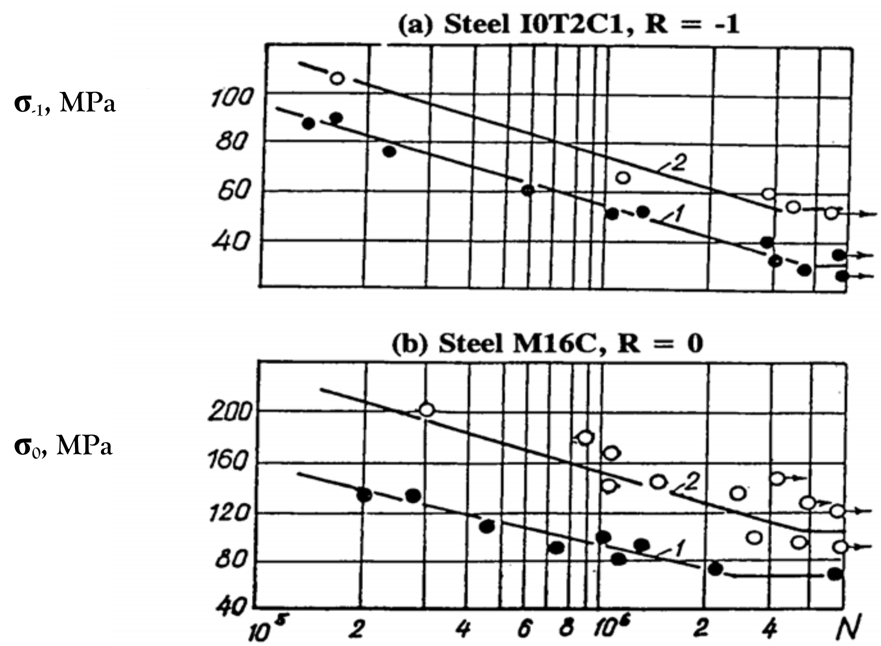


Figure 3.25 Improvements in Fatigue Strength of Welded Joints with Transverse Stiffeners Using the Explosive Treatment (Petushkov, 1993)

3.7 OVERLOADING TREATMENTS

3.7.1 Prior Static Overloading

This treatment relies on the introduction of compressive residual stresses at the weld toe as a result of local yielding. The positive effect of prior overloading has been observed in joints with both mild and severe stress concentrations. The efficiency of this method as a way of improving fatigue strength of welded joints depends on the value of the overloading stress, joint type and the value of the applied stress ratio. Experimental results indicate that the greatest increase in fatigue strength can be achieved by applying the highest possible overload stress, thus greater benefits can be obtained by treating higher strength steel structures rather than mild steel. Results reported by Trufyakov et al. (1993) show that the fatigue limit of a load-carrying member with an attached transverse stiffener is increased by 10%, 35% and 65% under applied tension loading of R = 0 as a result of overloading to levels of 0.5, 0.7 and 0.9 times the yield stress respectively. It should also be noted that regular periodic tensile overloading of the structure throughout its life may also be beneficial but the fatigue damage caused by these overload cycles must also be considered in the life calculation.

3.7.2 Local Compression

In this technique a small part of the structure is forced to yield locally by compression between circular dies. After the load is removed the plastic deformation of the material will cause residual compressive stresses to be induced around the indentation as shown in Figure 3.26.

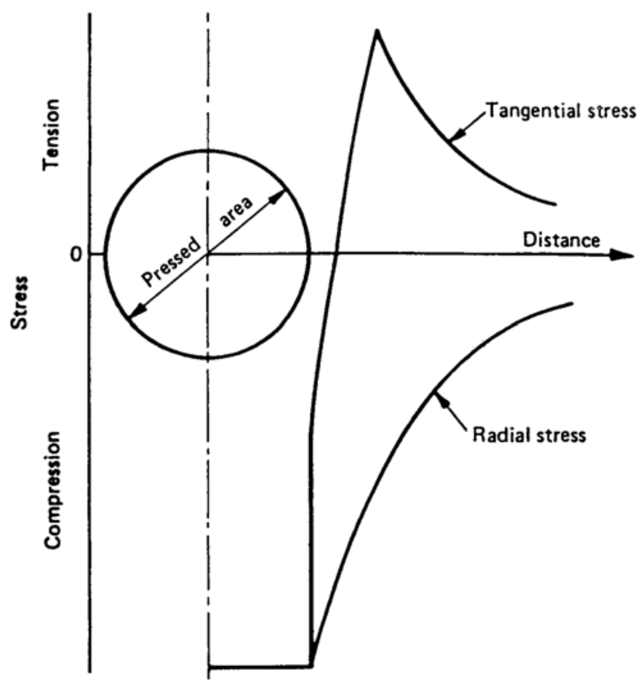


Figure 3.26 Theoretical Residual Stress Distribution Caused by Local Compression (Booth, 1991)

This procedure is well suited to details where the fatigue crack initiation site is known such as at spot welds or at the ends of longitudinal stiffeners as shown in Figure 3.27. It is not suitable for geometries such as transverse welded joints. A typical die diameter is 45 mm (1.75 in.) and a typical indentation is 0.18 mm (0.007 in.) deep, Booth (1991). Trufyakov et al. (1993) have reported that the fatigue limit of joints with longitudinal fillet welds can be increased by 70 to 100% when treated by this procedure. The main disadvantage of this local compression method is the high loads that must be applied at the dies and the need for access to both sides of the plate.

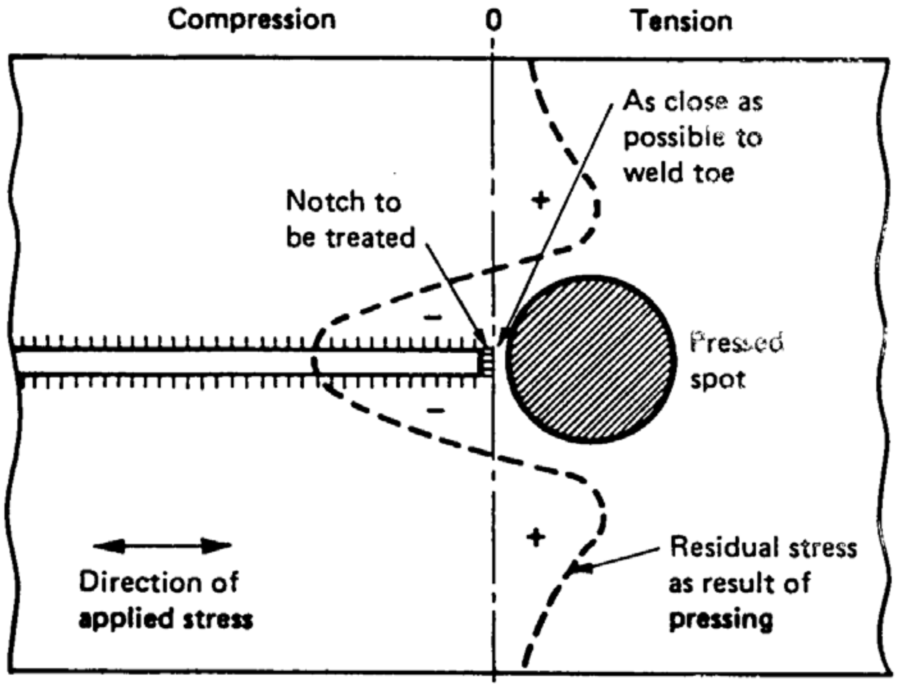


Figure 3.27 Recommended Position of Pressed Spot When Treating the End of a Longitudinal Gusset (Booth, 1991)

3.8 COMPARISON OF RELATIVE IMPROVEMENT PERFORMANCE OF TECHNIQUES

In this section of the report the relative improvement in fatigue strength achieved by each technique will be assessed as compared with as-welded (AW) joints. The improvement will be illustrated by S-N data from the literature where this is available. In most cases the increase in fatigue strength at 2 x 10^6 cycles will be assessed for direct comparison purposes[1].

3.8.1 Grinding Techniques

Grinding techniques are used as a method of improving the fatigue performance of welded components and structures in the offshore, shipbuilding and steel construction industries. As stated previously the benefit is derived from reducing the stress concentration by producing a favourable weld shape and by removing harmful defects and undercuts at the weld toe. Knight (1978) gives results for burr and heavy disc grinding as shown in Figure 3.28. Results for a mild steel and a high strength steel are shown in the figure[2]. The fatigue strength improvement for the higher strength steel is more dramatic. At the (relatively) high cycle end (about 5×10^5 cycles) an improvement in fatigue strength for the toe grinding is almost 100% over the as-welded condition; in the case of heavy disc grinding the improvement is a more modest 40%. The corresponding improvement for the mild steel is about 17% for both treatments.

Mohr et al. (1995) has completed a statistical analysis on some improvement techniques as applied to welded specimens with transverse attachment plates, and found that the improvement on fatigue life produced by grinding was a factor of approximately 2.2 which is in agreement with that given in BS 7608 (1993). The data for this analysis was obtained from offshore steel research programs in USA, Canada, United Kingdom, Europe and Norway.

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[1] The increase in fatigue life (for long lives, $N > 10^6$ cycles) can be found approximately from the increase in fatigue strength if it is assumed that the slope of the S-N curve does not change (ie. m=3). In such cases the following formula may be used:

$$(\text{Fatigue Life Ratio}) \approx (\text{Fatigue Strength Ratio})^3$$

For example, an improvement of 30% in fatigue strength will correspond to approximately an improvement of $(1.30)^3 = 2.20 \equiv 120\%$ improvement in fatigue life. Actual test data indicates that the slopes of the S-N curves for improved joints tend to increase. Hence the above relationship will be conservative for long lives, but may be unconservative for short lives ($N < 10^5$ cycles).

[2] It is assumed that certain of the curves in the figure have been mislabelled. It appears that "Heavy disc ground" and "Toe burr ground" for the mild steel (solid lines) have been transposed in error.

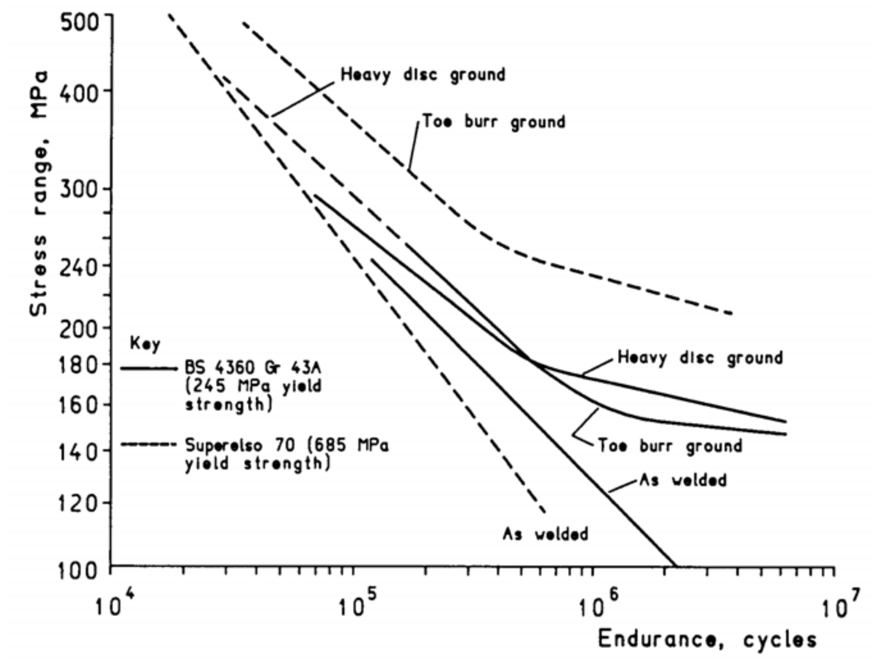


Figure 3.28 Fatigue Strength Improvements Due to Toe Burr and Disc Grinding (Knight, 1978)

An example from the literature on the effect of free corrosion in seawater on the fatigue strength of toe ground welds is shown in Figure 3.29, Booth, (1978). On the basis of these results the influence of corrosion is complex. For the as-welded specimens the influence on fatigue strength of corrosion is ambiguous. The high degree of scatter in the in-air results makes distinguishing this set of results quite difficult In contrast, there is a significant reduction in fatigue strength of toe ground specimens immersed in seawater compared with the corresponding results in air; the fatigue strength of specimens immersed in seawater is reduced by 20 to 30%.

3.8.2 Remelting Methods

Remelting of the weld toe region using a TIG or plasma torch generally gives significant fatigue strength improvements due to the production of a smooth transition between the plate and the weld metal. Typical results from tests on TIG dressed specimens are shown in Figure 3.8. The increase in fatigue strength in air at 2 x 10^6 cycles as compared with as-welded joints is approximately 100%. It does not appear that the improvement increases with increasing material tensile strength as shown in Figure 3.9. The reduced improvement as a result of seawater corrosive environment is shown in Figure 3.30. Mohr et al. (1995), from a statistical analysis of many tests, has obtained a factor of 2.2 for improvement in fatigue life for weld toes treated by TIG dressing.

Improvements obtained by TIG and plasma dressing compared with toe grinding and as-welded joints fabricated from high strength steels are shown in Figure 3.31.

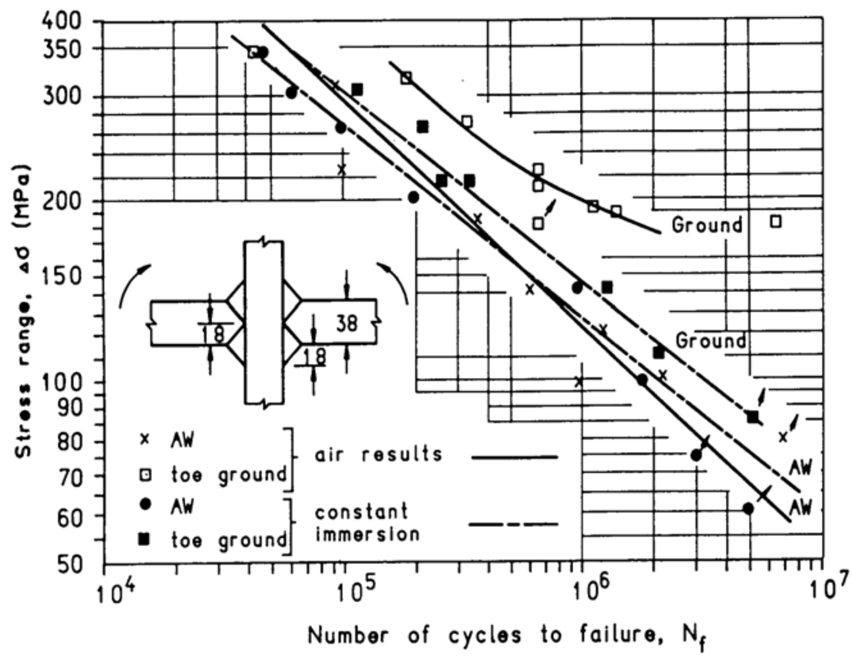


Figure 3.29 The Effect of Free Corrosion in Seawater on the Fatigue Strength of As-Welded and Ground Specimens (Booth, 1978)

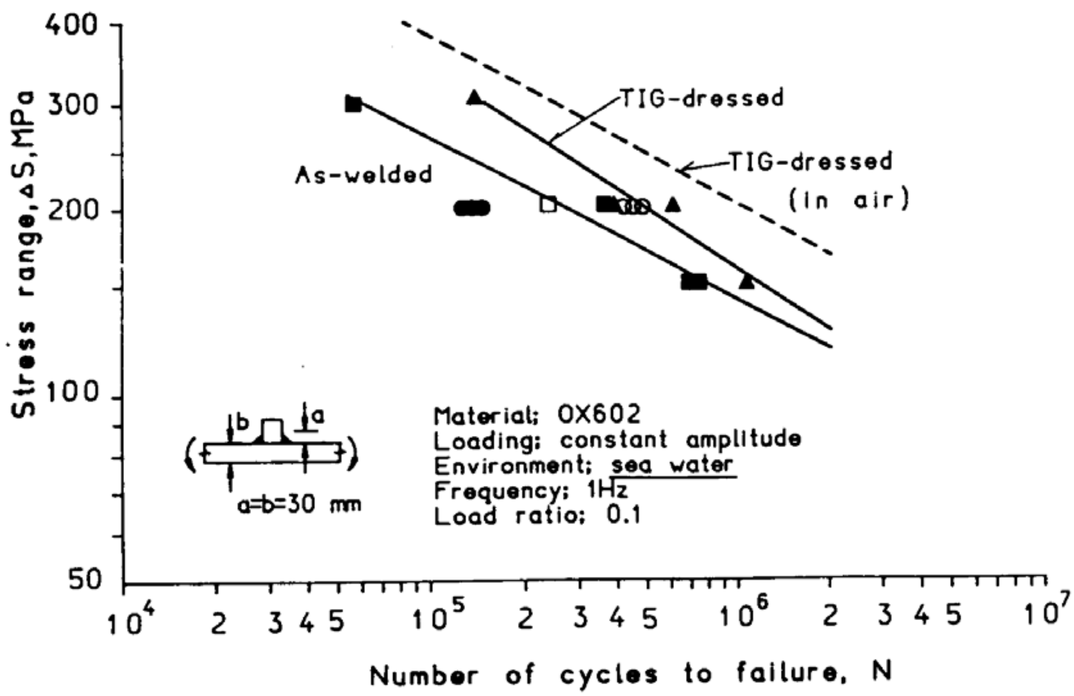


Figure 3.30 Influence of Seawater Corrosion on the Fatigue Strength of As-Welded and TIG-Dressed Specimens (Haagensen, 1981)

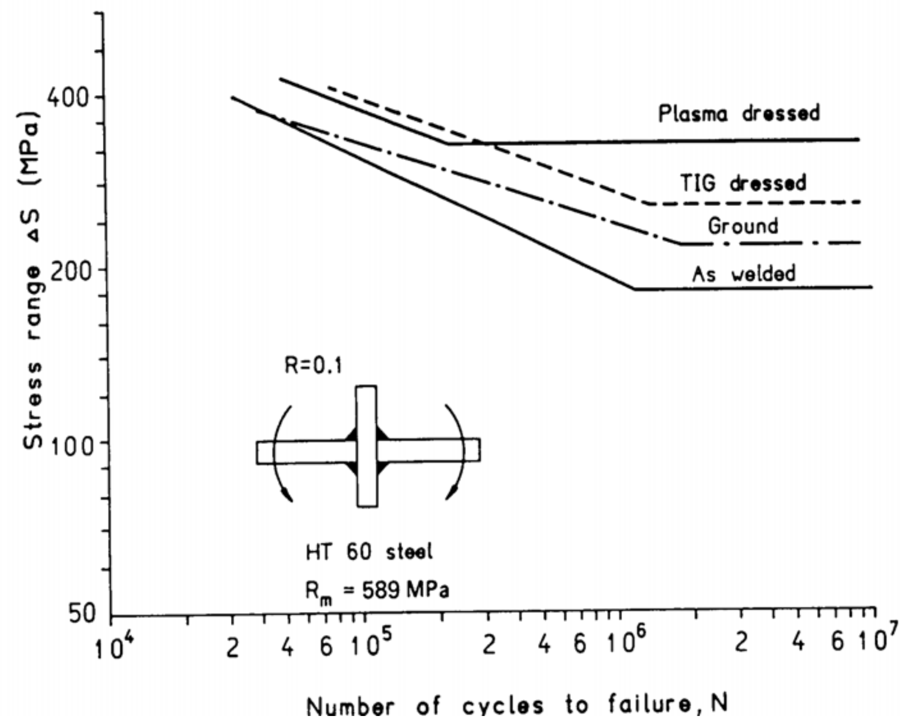


Figure 3.31 Effect of Some Improvement Methods Applied to High-Strength Steels (Shimada et al., 1977)

3.8.3 Profile Control

AWS improved profile welds are made according to the specifications of AWS D1.1 (1996), and meet the inspection requirements of the "dime" test, Figure 3.11. The benefits are obtained by a reduction in the stress concentration at the weld toe and an increased weld leg length. Results of joints with improved profiles are shown in Figures 3.12 and 3.13. The results show a significant improvement in fatigue strength particularly in the long life regime. Haagensen (1992) claims that there is a factor of 2 to 2.5 on life in this long life regime, but Mohr et al. (1995) in their analysis of the published data concluded that the improvement factor is less than the improvement allowed in current API RP2A guidelines for profile control. In the API RP2A guidelines the allowance for weld profile control is represented by the API X2 curve as compared with the higher API X1 curve which must be used for welds without profile control, Figure 3.13.

Profile control by the use of special electrodes was first developed in Japan as a way of improving the fatigue strength of steels with yield strengths ranging from 400 to 800 MPa (58 to 116 ksi). In this case fatigue strength improvements of 50 to 85% were obtained. Bignonnet et al. (1987) present results for plate joints using these electrodes as shown in Figure 3.16. The use of these electrodes for the finishing pass at the weld toe only have resulted in fatigue strength improvements of 60 to 80% as reported by Kado et al. (1975).

3.8.4 Peening Methods

Peening, whether by hammer, shot or ultrasonic impact is a cold working technique which replaces the tensile residual stresses produced by the welding process at the weld region by favourable compressive residual stresses. These compressive residual stresses effectively introduce a substantial initiation period in the fatigue life of the welded components.

Results showing fatigue strength improvements for hammer peened joints are given in Figure 3.18 by Haagensen (1985), and in Figure 3.19 by Booth (1977). Results for shot peened welds but with improved profile are given in Figure 3.14 by Bignonnet et al. (1984). Results for ultrasonic impact peening are given in Figure 3.20 by Trufyakov et al.(1993). The improvement in fatigue strength obtained by peening treatments are among the highest reported and are typically of the order of 50 to 200% for hammer peening, 30% for shot peening and 50 to 200% for ultrasonic impact peening. Figure 3.18 illustrates some of the dramatic improvements in fatigue strength that can result from peening. In some cases the improvement is so large that the weld is no longer critical and failure initiates in the base plate away from the weld, or in other cases for fillet welds the point of eventual failure moves from the weld toe to the weld root. The resulting failure is across the weld throat for which a possible remedy is to increase the size of weld.

3.8.5 Stress Relief Techniques

Post weld heat treatment (PWHT) is a process which primarily attempts to remove tensile residual stresses from the weld region and secondly may temper the microstructure, possibly improving the material toughness. The effectiveness of PWHT as a fatigue improvement method depends on the proportion of the applied stress cycle that is compressive. Unfortunately in many cases tensile residual stresses of up to 30% of yield may remain after PWHT. Therefore, in view of this uncertainty, no beneficial effect can be claimed with regards to fatigue strength improvement.

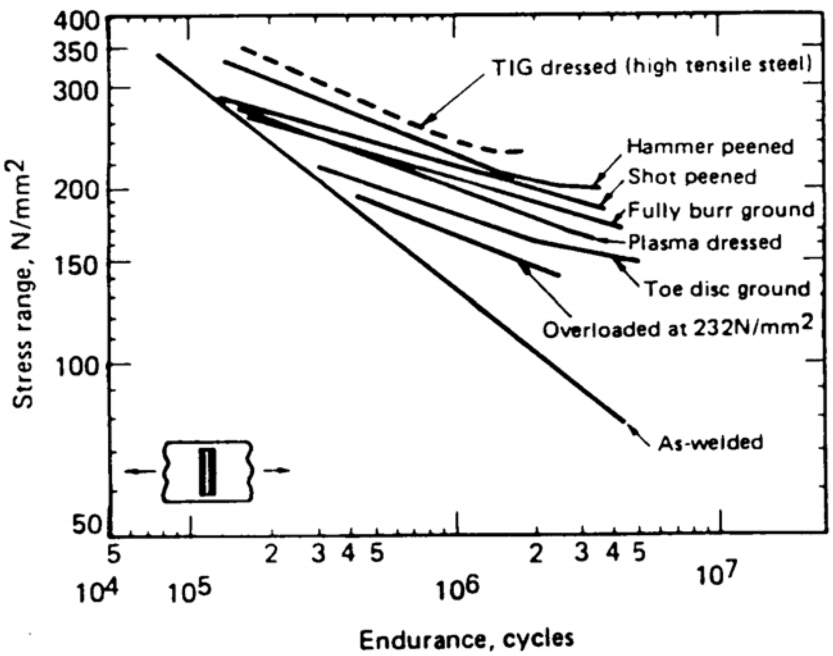
The improvements in fatigue strength resulting from a spot heating treatment on a plate with a welded edge attachment are shown in Figure 3.23. The improvement in fatigue strength at 2×10^6 cycles is of the order of 100%. However, difficulty in positioning the spot, the specialized equipment required and the limitations on the joint type and accessibility make this treatment of limited applicability in ship structures.

Results for the fatigue strength improvement of welded joints with transverse stiffeners, treated with the explosive method and compared with as-welded joints, are shown in Figure 3.25. The improvement in fatigue strength obtained for the two steels shown are of the order of 50%, however, the nature of this treatment makes it impracticable for ship structures.

3.8.6 Overloading Treatments

The improvement in fatigue strength of transverse fillet-welded joints is shown in Figure 3.32. It can be seen that the beneficial result of overloading treatment is relatively small in comparison to other techniques. The overloading treatment can generally be considered as a "last chance" technique. The large loads required for full size ship structure assemblies and possibility of inflicting damage elsewhere in the structure make this procedure impracticable for ship structures.

Figure 3.32 Effect of Improvement Techniques Applied to Mild Steel Transverse Non-Load-Carrying Fillet Welded Joints (Booth, 1991)



Similarly the local compression technique, while it apparently gives good results for high strength steels, can only be considered as perhaps a repair treatment. The large loads necessary and the accessibility requirements (i.e., both sides of a plate welded joint) make this treatment of limited application in ship structures.

3.8.7 Combination of Improvement Methods

It has been shown that compounding of improvement techniques can give very large improvements in fatigue strength. In general, these should only consider the combination of a weld geometry improvement method with a residual stress method (e.g., toe grinding and hammer peening, but not toe grinding and TIG dressing). This approach is expensive but can be used in situations where costs are of secondary importance such as repair of a damaged structure or in cases where extensive redesign of the structure to meet fatigue requirements is to be avoided.

Gurney (1968), Figure 3.34, combined full profile grinding and hammer peening to produce results which restored the fatigue strength of the mild steel fillet welded joints to the level of the base material.

Bignonnet et al. (1984), Figure 3.13, presented results for joints with improved weld profile produced by special electrodes and treated with shot peening. Haagensen (1993), Figure 3.35, combined weld toe grinding with hammer peening and obtained an increase in fatigue strength at 2 x 10^6 cycles of 216%. In this test program specimens with simulated cracks were also repaired and the repaired joints treated with toe grinding and peening. The results of these repaired joints demonstrated that the fatigue performance of the repaired joints exceeded that of toe ground joints.

3.8.8 Summary of Relative Fatigue Strength Improvements

Most of the techniques discussed above are compared for mild steel joints (yield stress 245 MPa or 36 ksi), in Figure 3.32 and Figure 3.33. The results shown in Figure 3.32 are for a transverse non-load-carrying joint and Figure 3.33 presents results for joints with a fillet welded longitudinal gusset. Together these figures present graphically the relative improvement which can be obtained in fatigue strength by the application of the techniques described in the previous sections. In general it can be seen that at high stress levels little improvement in life is observed, however at lower stress levels the improvement can be significant.

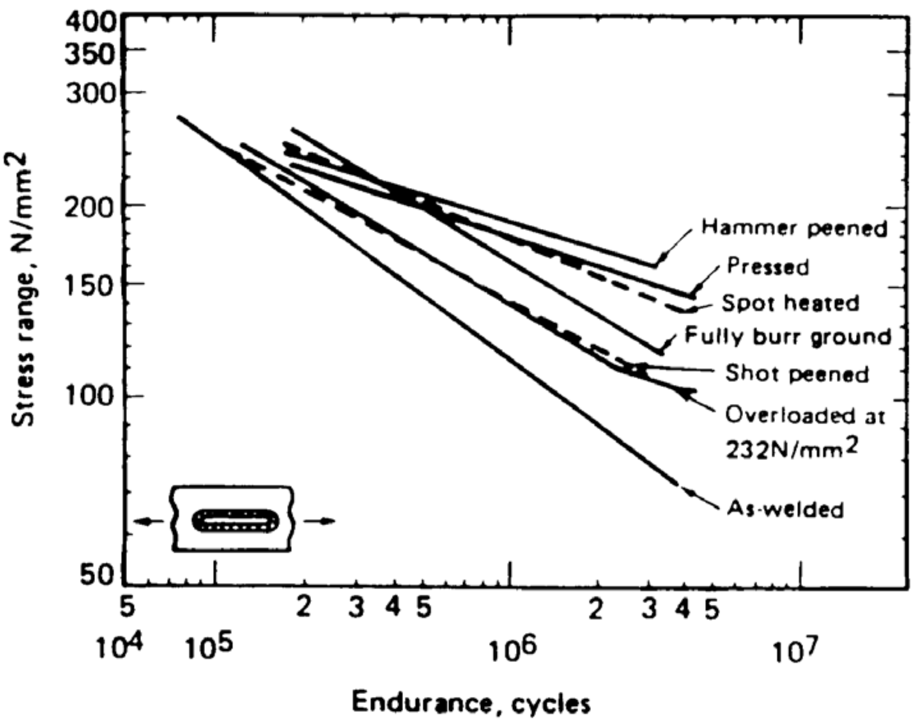


Figure 3.33 Effect of Improvement Techniques Applied to Mild Steel Fillet Welded Longitudinal Non-Load-Carrying Joints (Booth, 1991)

Huther et al. (1994), performed a very comprehensive statistical analysis of over 300 sets of data compiled from various investigators for weld toe grinding, TIG dressing, hammer peening and shot peening treatments. The data considered butt joints, T joints, cruciform and longitudinal non-load carrying joints less than 25 mm (1 in.) thick in non-corrosive (air) environment. The data was sorted according to type of treatment, yield strength, type of joint, and stress ratio. Some of the conclusions of the analysis are as follows:

- With the exception of weld grinding of T-joints, all curves are above the as-welded joint curves defined by Eurocode 3, 1984.

- In the case of grinding, with a lack of optimization, the results can be lower than the as-welded curve for T-joints.

- Hammer peening gives the greatest benefit for cruciform and longitudinal joints.

- All techniques give approximately similar improvement levels for butt joints.

- The S-N curves of improved joints in high tensile steel (YS > 400 MPa) are above or equal to those of improved joints in mild steel.

- All slopes (Δlife/Δstress) are greater than 3 which is the slope for as-welded steel.

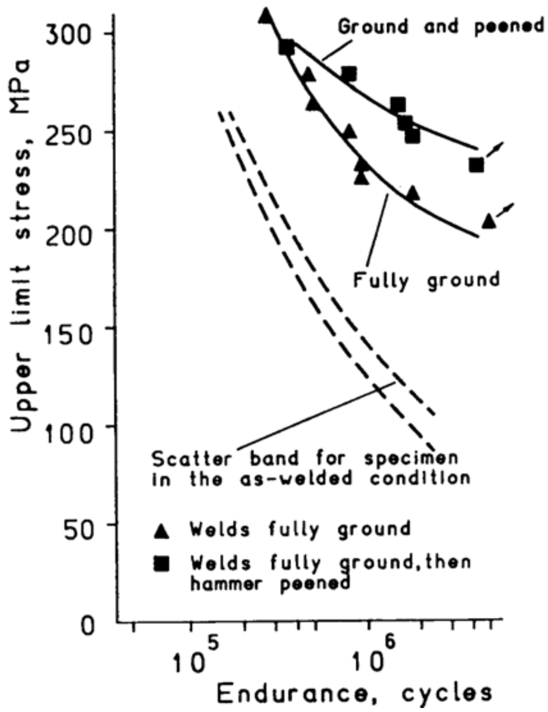


Figure 3.34 Fatigue Strength Improvement Obtained by Compounding Grinding and Hammer Peening (Gurney, 1968)

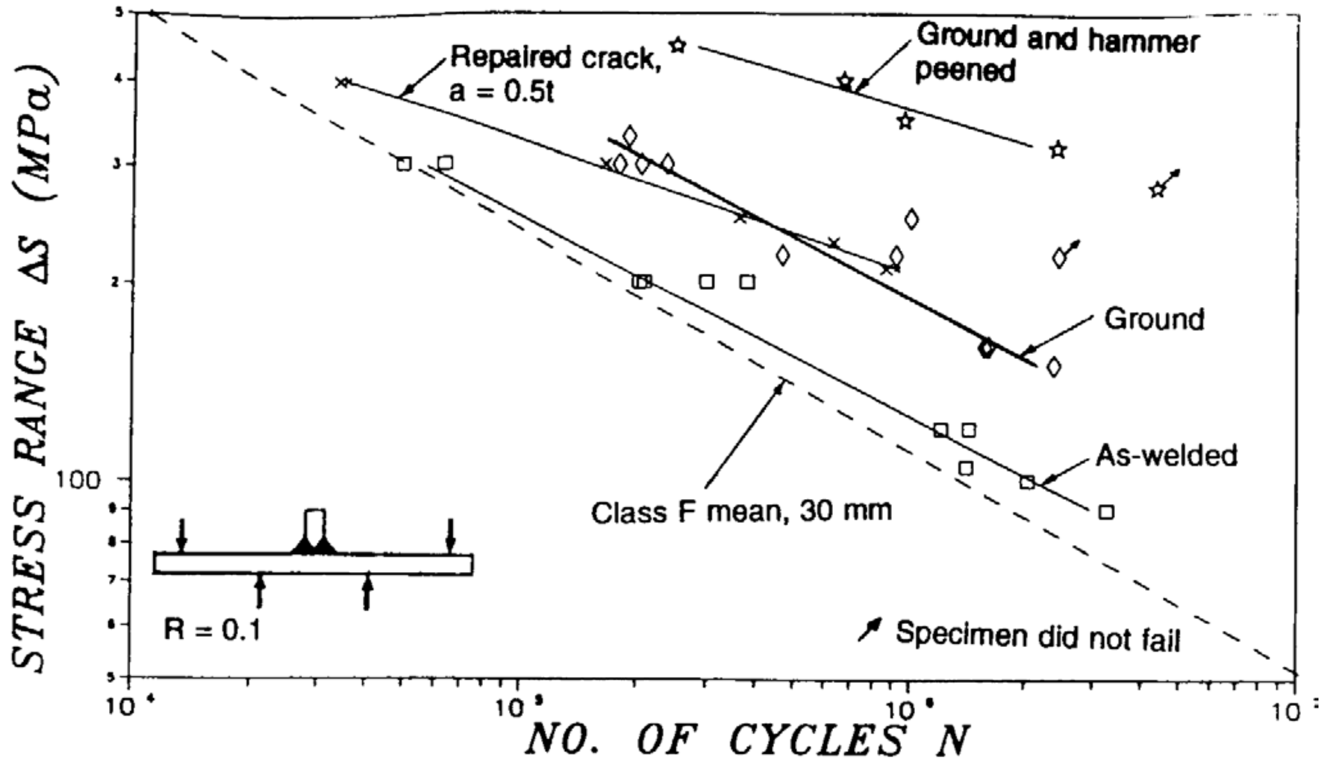


Figure 3.35 Comparison of S-N Curves for As-Welded, Toe Ground, Repaired and Ground and Hammer Peened Specimens (Haagensen, 1993)

3.9 RELATIVE COSTS

The application of most fatigue life improvement techniques are time consuming and therefore are quite expensive. A summary of the relative costs of each technique as obtained from the literature is given in Table 3.1. Large uncertainties are associated with the figures in this table because it is not clear if the application speed or relative costs include the labour costs of performing the operation or if the figures also include the costs of additional equipment necessary or the time and cost associated with inspection and quality control to ensure that the treatment has been correctly performed. Thus the data presented in Table 3.1 should be used more for relative comparison purposes rather than absolute costs. Section 4 of this report presents more realistic costs for burr grinding, TIG dressing and hammer peening fatigue improvement treatments which are most applicable to the shipbuilding industry.

Table 3.1 Summary of Relative Costs of Improvement Techniques

Weld Life Improvement Technique	Typical Application Speed (in / min)	Typical Application Speed (mm / min)	Relative Costs [1]
1. Weld Modification Techniques			
1.1 Burr Grinding	2 - 4	50 - 100	6 - 18
1.2 Disc Grinding	0.5 - 1.5	10 - 40	2 - 4
1.3 Water Jet Eroding	12 - 30	300 - 750	-
2. Weld Toe Remelting Techniques			
2.1 TIG Dressing	3 - 6	75 - 150	3
2.2 Plasma Dressing	faster than TIG		-
3. Special Welding Techniques			
3.1 AWS Improved Profile	-	-	-
3.2 Special Electrodes	-	-	(cost of electrodes)
4. Peening Methods			
4.1 Shot Peening	-	-	1.5
4.2 Hammer Peening	10 - 20	250 - 500	1
4.3 Needle Peening	-	-	0.5
4.4 Ultrasonic Impact	20	500	-
5. Stress Relief Methods			
5.1 Thermal Stress Relief (PWHT)	-	-	-
5.2 Vibratory Stress Relief	-	-	-
5.3 Spot Heating	-	-	2
5.4 Gunnert's Method	-	-	-
5.5 Explosive Treatment	-	-	-
6. Overloading Treatments			
6.1 Prior Static Overload	-	-	-
6.2 Local Compression	-	-	-

Note: "-" indicates data not available.
[1] Costs are relative to hammer peening treatment.

3.10 SUMMARY OF ADVANTAGES AND DISADVANTAGES

A summary of the advantages and disadvantages of the fatigue improvement techniques is given in Table 3.2. Burr and disc grinding are the most widely used improvement techniques and are currently the only improvement methods allowed for in the European codes for the design of offshore structures, Health and Safety Executive UK (1992) and DNV (1984). The equipment is readily available in ship fabrication facilities and the operator skill level requirements are not excessive, however the process is expensive. Water jet eroding is very fast compared with other techniques, however it is difficult to control the rate of erosion which may result in detrimental damage to the weld.

Table 3.2 Summary of Advantages and Disadvantages of Improvement Techniques

Weld Life Improvement Technique	Advantages	Disadvantages
1. Weld Modification Techniques	Relatively simple to perform. Large improvement. Simple inspection criteria (depth 0.020 in / 0.5 mm below plate surface or undercut).	Applicable mainly to planar joints that can be expected to fail at weld toe. May lose benefit if not protected from corrosion. All grinding techniques give a poor working environment regarding noise and dust. Access to weld may be a limiting factor.
1.1 Burr Grinding	Most effective of all grinding methods with large and repeatable improvement. Equipment readily available. Easier accessability than disc grinding. Best for fillet welds.	Very slow. Expensive due to high labour costs and high tool wear rate - many consumables. Difficult to maintain quality. Surface scaling may reduce benefit.
1.2 Disc Grinding	Very fast compared to burr grinding. Can cover large areas. Equipment readily available.	Score marks give lower improvements than burr grinding. Improper use may introduce serious defects - risk of over grinding. Restricted applicability due to tool size.
1.3 Water Jet Eroding	Very fast compared to other fatigue improvement techniques. Good potential for automation.	Equipment not readily available in most shipyards. Difficult to control rate of erosion - severe risk of over abrasion. Cleanup of water and abrasive particles may limit application.

Table 3.2 Summary of Advantages and Disadvantages of Improvement Techniques (Cont)

Weld Life Improvement Technique	Advantages	Disadvantages
2. Weld Toe Remelting Techniques	Large improvements are possible. Equipment readily available in most shipyards. Suitable for automation and / or to incorporate as part of welding procedure.	Operator needs special training.
	Large improvements achieved. Small	Careful cleaning of weld and plate

2.1 TIG Dressing	physical effort required. Inexpensive.	necessary. Risk of local HAZ hardening (cracking) in C-Mn steels due to low heat input - may require second TIG run.
2.2 Plasma Dressing	Easy to perform due to large weld pool. Similar or larger improvement than TIG dressing with smaller risk of HAZ hardening.	Careful cleaning of weld and plate necessary.
3. Special Welding Techniques	Improvement is introduced in the welding process itself.	Defects at weld toe not removed.
3.1 AWS Improved Profile	Well defined inspection criteria ("dime test"). Suitable for large multi-pass welds.	Very large scatter in test results due to variations in micro- geometry at weld toe. Consistent improvement only possible if combined with other improvement techniques (eg. grinding or peening). Not suitable for small welds.
3.2 Special Electrodes	Easy to perform. Suitable for small joints. Inexpensive.	Doubtful benefit - only small improvement at best. Electrodes not widely available.
4. Peening Methods	Large improvements possible. Greatest benefits obtained with high strength steels.	Not suitable for low cycle (high stress) fatigue applications. Beneficial effects may disappear under variable amplitude loading involving peak compressive loads.
4.1 Shot Peening	Well developed procedures for small parts. Covers large areas. Simple methods for quality control (Almen strip). Improves resistance to stress corrosion cracking.	Special equipment required. Messy - cleanup of shot. Practical application to large scale structures not demonstrated. Best suited for mild notches and very localized areas with good access. Corrosion may quickly remove beneficial effects since only a very thin surface layer of plate is deformed.

Table 3.2 Summary of Advantages and Disadvantages of Improvement Techniques (Cont)

Weld Life Improvement Technique	Advantages	Disadvantages
4.2 Hammer Peening	Good repeatable benefits. Very large improvements possible for poor quality welds. Simple inspection criterion (depth of groove >0.024 in or 0.6 mm). Equipment readily available.	Noisy and tedious - may restrict use to "off hours" in shipyard. Limited to toe treatment only. Excessive peening may cause cracking. Some restrictions due to tool size.
4.3 Needle Peening	Similar to hammer peening, but improvement less established.	Similar to hammer peening.
4.4 Ultrasonic Impact	Similar to hammer peening, without noise and operator fatigue problems.	Special equipment required.

5. Stress Relief Methods		Not suitable for low cycle (high stress) fatigue applications. Beneficial effects may disappear under variable amplitude loading involving peak compressive loads.
5.1 Thermal Stress Relief (PWHT)	Well characterized.	Doubtful benefit. Limited applicability to large components - needs very slow cool. Specialized equipment required. Used more for "dimensional stability" than for fatigue improvement.
5.2 Vibratory Stress Relief		Doubtful benefit. Limited applicability to large component. Specialized equipment required.
5.3 Spot Heating	Good repair technique. Equipment readily available. Best for large plates.	Only for very localized areas. Must know crack site. Not effective for transverse welds. Very thick plates may require excessive energy.
5.4 Gunnert's Method	Not necessary to know crack initiation point. Strict temperature control not necessary.	Specialized equipment required. High temperatures (1020 °F / 550 °C). Cooling must be localized - may not be suitable for large (or very small) joints. Excessive heat may cause martensitic transformation upon cooling.
5.5 Explosive Treatment	Faster and cheaper than heat treatment techniques. Does not require specialized equipment nor highly skilled personnel.	Dangerous. Quality control difficult. Doubtful application in shipyard.

Table 3.2 Summary of Advantages and Disadvantages of Improvement Techniques (Cont)

Weld Life Improvement Technique	Advantages	Disadvantages
6. Overloading Treatments		
6.1 Prior Static Overload	Good benefits for high strength steels. Applicable to cracked structures.	"Last chance" technique. Special equipment needed. Enormous loads required for full size ship structure assemblies. Application limited to small components.
6.2 Local Compression	Good benefits for high strength steels.	Specialized equipment needed. Access to both sides of plate needed. Only suitable for very localized areas.

Weld toe remelting techniques give substantial improvements, are relatively inexpensive and are suitable for automation. The equipment necessary to carry out these treatments are available in most shipyards, however the operator needs special training and qualification procedures may be necessary to ensure that the procedure is carried out correctly to obtain maximum benefit.

Peening techniques give the highest fatigue strength improvement benefit and the equipment necessary for application of hammer, needle and shot peening are readily available in most shipyards, however the noise and operator fatigue are major impediments to the widespread use of these techniques. Current developments in the design of new quiet and vibration isolated hammers may remedy this lack of widespread use. Ultrasonic impact peening appears to overcome some of the disadvantages of the other peening techniques, however special equipment is required.

In the main, stress relief methods are not suitable as fatigue life improvement treatments in the shipbuilding industry. PWHT is of limited use as an improvement technique and its benefit is very dependent on the applied stress level. Vibratory stress relief, Gunnert's method and explosive treatments are not applicable in a shipyard environment. Spot heating may be of limited use particularly in repair situations.

Overloading treatments give reasonable benefits when applied to laboratory test specimens particularly for high strength steels, however, the application to full size ship structures require specialized heavy equipment and thus the use in shipyards is unlikely to be considered.

Of the various techniques, weld grinding, weld profiling, TIG dressing and hammer, needle and ultrasonic peening appear to hold the best potential for ship structure applications. Each of these techniques provide a significant and repeatable improvement in fatigue strength and involve equipment and procedures that are familiar to shipyards.

Stress relief techniques including PWHT, vibratory stress relief, Gunnert's method and explosive treatments do not appear to be practical for ship applications. For these techniques, the fatigue strength improvement benefit is minimal and / or the procedures involved are simply not possible in a shipyard environment.

Other techniques including spot heating and local compression may hold some potential as treatments for specific repairs details.

Due to the expense of the application of these techniques, it is suggested that they should be considered primarily as remedial actions or treatments used in repair situations rather than procedures specified in the design of new structures. At the design stage, these treatments should only be considered as a last resort if the designer cannot modify the joint in question to achieve the desired fatigue performance for the over structure.

4.0 APPLICATION OF WELD IMPROVEMENT TECHNIQUES TO SHIPS

4.1 INTRODUCTION

As outlined in Section 3, a substantial amount of research has been carried out on the relative benefits of fatigue strength improvement methods for welds. The technical feasibility of various techniques has been investigated in numerous laboratory experiments and, to a more limited extent, in the field. As a result several methods have been included in design codes for highway and rail bridges and offshore structures as approved procedures for improving critical joints and to avoid extensive redesign when a damaged structure has been repaired. A key question is whether these techniques can successfully be applied to ship structure and, if so, can this be done in a cost effective manner. A related question concerns the practicality of these methods.

The techniques that are most mature in industrial applications, and appear to offer the most potential for ship structure applications, include the weld toe grinding, TIG dressing, and hammer peening treatments as well as combinations of these treatments. To date, however, there has been only limited application to ship structures, primarily with regards to crack repairs. A survey of shipyards has indicated that procedures such as weld grinding, TIG dressing and weld peening are currently applied only in special circumstances, or where there is no other real repair alternative. The additional cost involved is an overriding concern for shipyards for new constructions; any procedure which is not cost effective is not likely to be adopted even if fatigue strength improvements are substantial. It also appears that in many cases there is a lack of standard procedures for applying weld improvement techniques in shipyards.

In terms of implementing such techniques, guidance is therefore needed for all those concerned with the structural integrity of ships. There are several variables to be considered in making decisions in regard to the application of fatigue life improvement techniques. These may include:

- type of joint;
- steel and weld properties;
- welding process;
- welding configuration (eg., downhand);
- manual or automatic welding;
- equipment available;
- access;
- inspection and quality control;
- operator skill and training; and
- costs.

These and other factors may need to be considered in determining the practicality of applying fatigue life improvement techniques.

This chapter provides guidance on the application of the burr grinding, TIG dressing and hammer peening techniques for improving the fatigue life of welded ship details. These techniques are considered to have the most potential for ship structure details. Optimum procedures for the application of these techniques are presented, based on the IIW Commission XIII Working Group 2 specification by Haagensen and Maddox (1995). Tests on the practical application of these techniques on a representative ship structure detail are also presented and used to develop factors for estimating costs.

The specifications have not been adopted. They are draft specifications for a round robin test program on improvement technique sponsored by IIW Commission XIII Working Group 2. It is expected that these specifications will be published after the results of the round robin exercise are evaluated (sometime in 1997).

4.2 BURR GRINDING

4.2.1 Applications

The burr grinding treatment may be applied for new constructions or for improving the repair life of welds. As discussed in section 3.2.1, burr grinding is aimed at removing small crack-like defects at the weld toe, thereby introducing a significant crack initiation delay. A secondary benefit in terms of fatigue performance is achieved by reducing the notch stress concentration at the weld toe. Since the improvement in fatigue strength is due to a modification in the conditions at the weld toe, the burr grinding technique should only be considered as a treatment for weld details where failure can be expected to occur at the weld toe. Obviously no improvement can be expected if the untreated joint is as likely to fail from the weld root as the weld toe; the failure in the treated joint would only be shifted to the root as illustrated in Figure 4.1.

Burr grinding is most successful when applied to the following basic types of detail (see Figure 4.2):

a) Transversely loaded butt welds (welded from both sides); and
b) Transversely loaded full penetration T-joints and cruciform joints.

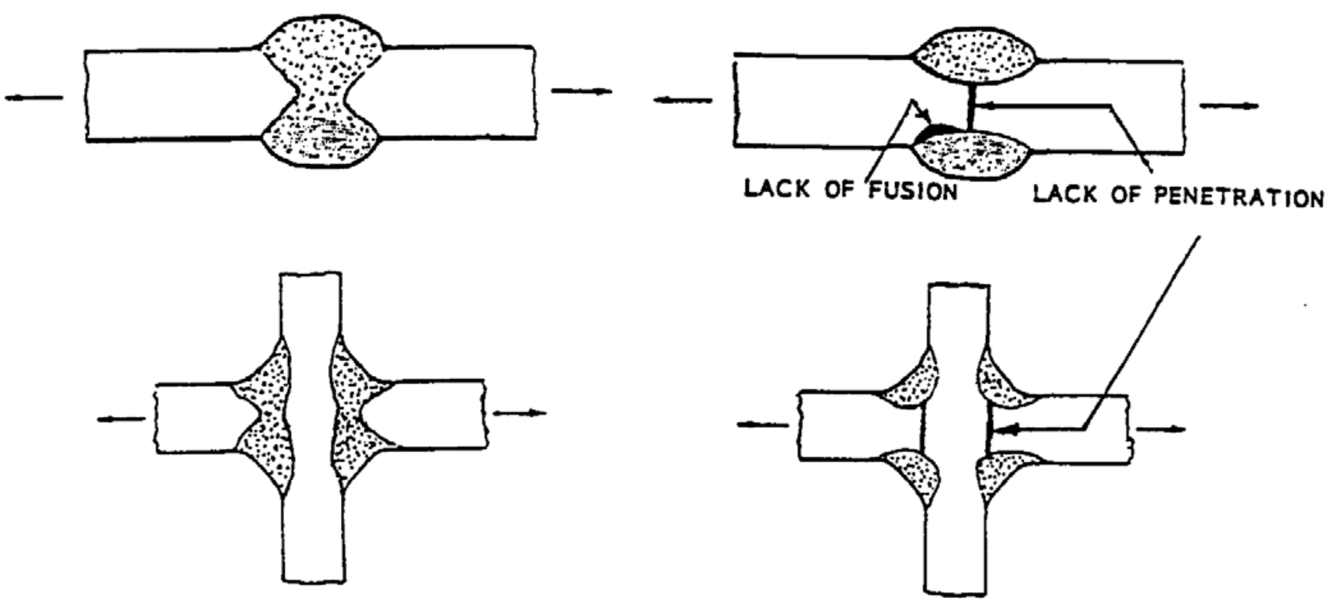
It should be noted that transverse butt welds with the profile ground flush with the plate surface should not be assumed to obtain any additional benefit from burr grinding of the weld toe.

Because burr grinding introduces groove marks in the direction transverse to the weld which can serve as crack initiation sites, it is not recommended as a treatment for welded joints that are loaded in a direction parallel to the weld, for example:

a) Longitudinally loaded butt weld (oriented parallel to the main stress direction);
b) Longitudinally loaded groove welds;
c) Longitudinally loaded fillet welds (both continuous and intermittent);
d) Longitudinally loaded weld terminations.

Due to the uncertainty about the initiation site of the fatigue crack, caution should be used when considering applying burr grinding improvement techniques to the following types of basic welded details:

a) Transverse butt welds made from one side and those made onto permanent backing;
b) Connectors and studs;
c) Cruciform and T joints with partial penetration butt or fillet welds;
d) Coverplates;
e) Lap joints.



a) Joints Most Suitable for Improvement   b) Joints Less Suitable for Improvement

Figure 4.1 Alternative Failure Locations of Welded Joints

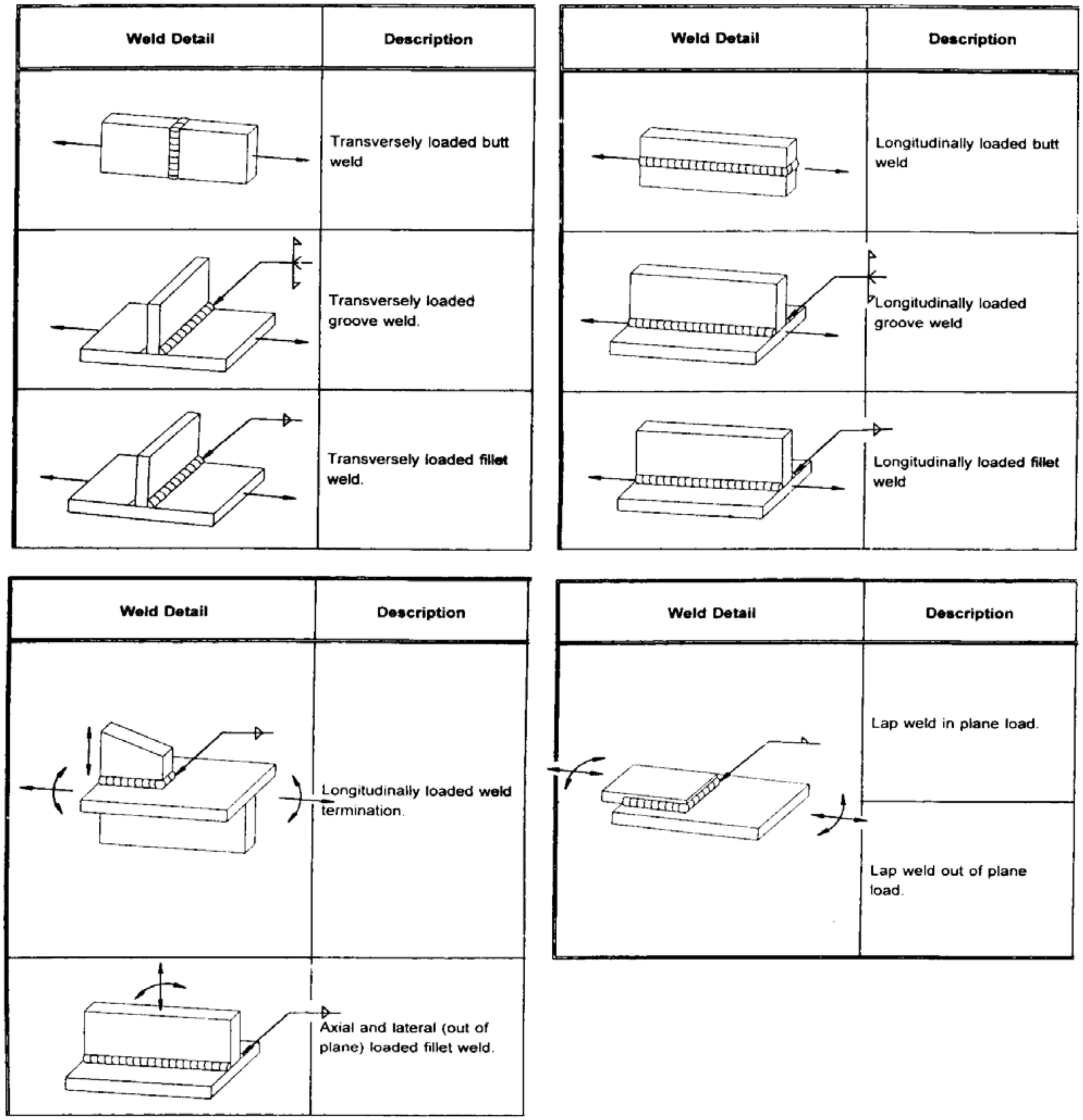


Figure 4.2 Basic Weld Details (Stambaugh et. al., 1994)

If applying weld toe fatigue improvement techniques to these types of details, checks should be made to ensure that fatigue failure will not first occur at the weld root or other site in the weld detail. For example, if applying a weld toe treatment to a partial penetration fillet weld or lap joint, the fatigue strength of the weld toe will increase but the fatigue life of the joint may not increase as much as expected because failure may move to the weld root. In practice, it is possible to ensure that root failure will not occur by providing an adequate weld size (throat dimension) in partial penetration joints.

It is further recommended that the minimum plate thickness for implementation of toe grinding improvement techniques be 10 mm (3/8 in.). This is because at thinner thicknesses, removal of 0.5 mm of material at the weld toe represents a fairly significant (5%) reduction in the load bearing cross sectional area, thus increasing the stress levels and possibly increasing the susceptibility to other modes of failure (plastic collapse, buckling).

4.2.2 Fatigue Strength Improvement By Burr Grinding

The current status of the incorporation of burr grinding (as well as TIG dressing and hammer peening) improvement methods into design rules and guidance notes is limited. To date, there are no universally accepted design S-N curves for these techniques. However, several research projects are currently underway which should hopefully remedy the situation in the near future. Of particular relevance to this project is the IIW Commission XIII - Working Group 2 collaborative testing program, involving 12 laboratories in 10 countries, three improvement techniques (burr grinding, TIG dressing, and hammer peening) applied to a TMCP steel (420 MPa yield strength). The results of this program should be available in 1997.

Of the various design codes, the UK Health and Safety Executive (1992) guidance rules allow application of a factor of 1.3 on strength (2.2 on life) on the S-N curves of all types of joints if grinding is performed. The slope of the S-N curve remains fixed at 3. The Det Norske Veritas (1995) fatigue assessment procedure permits an increase by a factor of 2 on fatigue life by local grinding of the weld toe. Lloyd's fatigue assessment procedure (1996) suggests the amount of increase in fatigue strength depends on the grinding process used and can be estimated to be of the order of at least 50% in the high cycle region. However, the quantitative improvement in fatigue life should be agreed with LR based on existing experimental data.

In summary, an increase in fatigue strength of the order of 30% above that of the as-welded design S-N curve, with no change in slope of the curves (ie. m=3), may be assumed as a conservative lower bound, Haagensen (1996). This corresponds to approximately a 120% increase in the fatigue life, provided the life of the as-welded joint is greater than 10^6 cycles. The improvement in fatigue strength is independent of the tensile strength of the steel (Vosikovsky, 1992). Higher levels of fatigue strength improvement should be justified based on experimental data for similar types of joints and steels.

4.2.3 Corrosion Protection

Current design codes impose a penalty factor which reduces the fatigue life or operating stress for untreated joints operating in seawater. It has also been shown in the literature that joints tested in a corrosive environment may also have reduced benefit from toe grinding (and other weld improvement) treatments.

Booth (1987) presented results which demonstrate the effect of a corrosive environment (artificial seawater) on the fatigue life of weld ground joints fabricated from a 350 MPa yield strength steel. The tests were carried out at a stress ratio of R = 0, a testing frequency of 1/6 Hz and a water temperature between 5 to 8°C. Some of the joints were pre-corroded for approximately six weeks by exposure to the atmosphere. Each week individual specimens were also sprayed with seawater. The results of these tests performed in seawater immersion in free corrosion and with optimum cathodic protection are shown in Figures 4.3 and 4.4. On the basis of data presented in the latter figure it can be seen that under free corrosion conditions the benefit of weld toe grinding is removed and the performance is inferior to that of joints loaded in air. This has been explained by the corrosive action of seawater causing general surface roughening and pitting of the smooth profile of the ground area which provides for easy crack

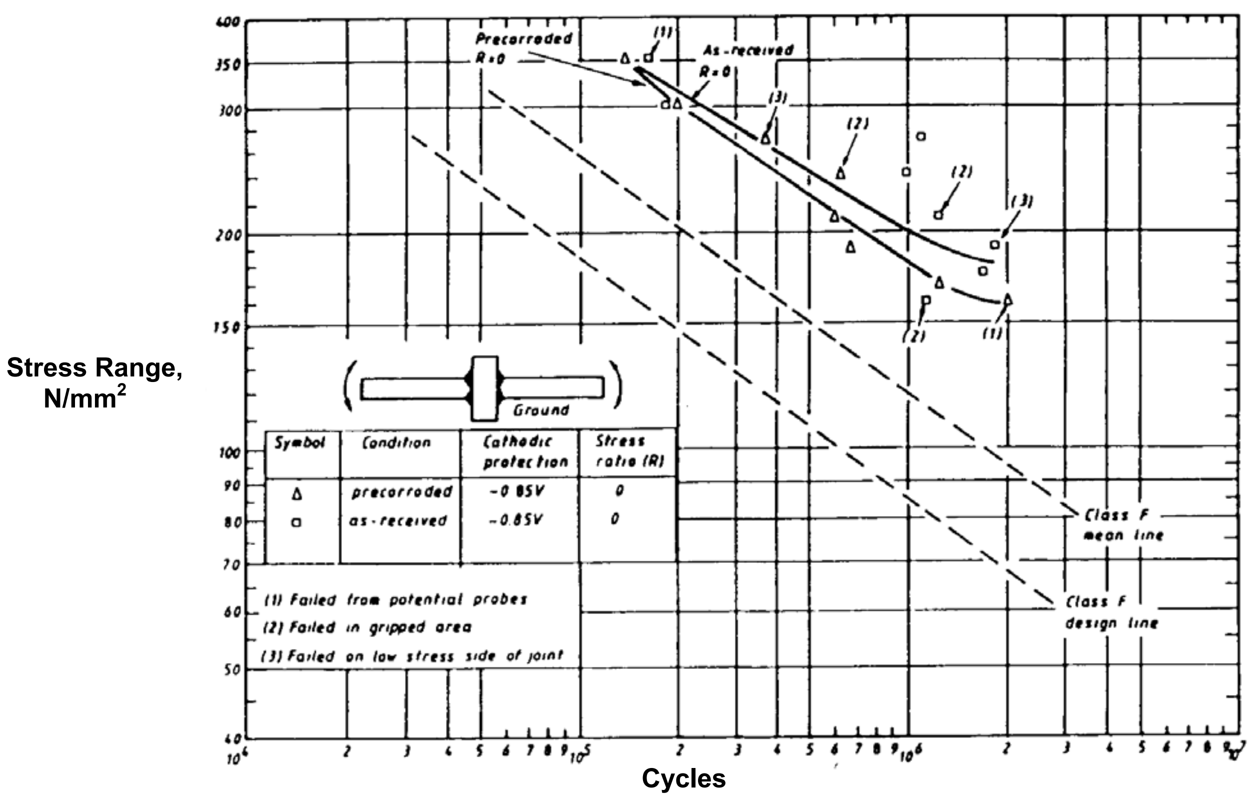
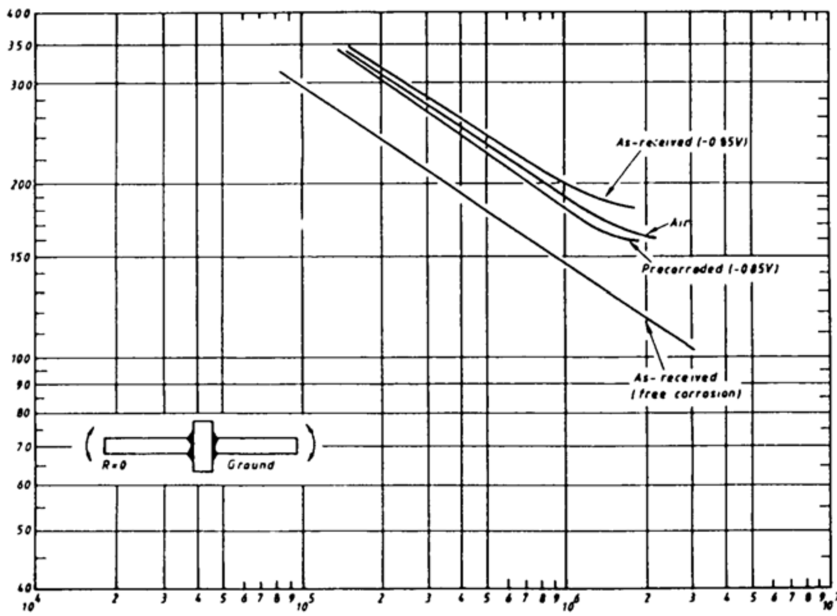


Figure 4.3 Fatigue Tests for Ground Joints (Booth, 1987)



Stress Range, N/mm^2

Cycles

Figure 4.4 Summary of Effects of Precorrosion and Environment on Ground Joints (Booth, 1987)

initiation early in the life of the joints. However testing at optimum cathodic protection conditions restores the performance to the in-air results. It can also be seen that the pre-corrosion period caused a small reduction in fatigue life, when subsequent testing was carried out with cathodic protection.

Matsumoto et al. (1989) presented similar findings for welded joints with weld toe grinding treatments fabricated from four steels with yield stresses of 372, 465, 481 and 764 MPa. The results from this series of tests for as-welded, in air, free corrosion and cathodic protection are given in Figures 4.5 - 4.8. Matsumoto et al. also gave a plot of the variation of fatigue strength of these steels under free corrosion and cathodic protection conditions vs tensile strength of the base metal which is shown in Figure 4.9.

The corrosion protection systems used on ships include protective coatings and sacrificial anodes. Coatings are paints to prevent metal from direct contact with corrosive elements such as seawater. The paints used widely in marine conditions are "twopack" epoxy coatings. Two-pack means that these paints are prepared by mixing two components before application. These two components are mixed just before use and after application the paint cures to a hard durable coating by chemical reaction. In most cases welds require some degree of grinding or blast cleaning to remove pinholes, sharp projections and undercuts which may protrude through the paint films or result in poor attachment of the coating to the surface. As such, this can be a good opportunity for grinding and smoothing out weld defects to not only improve the application of the protective coating, but also to improve fatigue strength.

It should be noted that in the case where weld grinding is performed as a preparation for the application of protective coatings, care should be taken to ensure that the fatigue performance of the weld is not adversely affected. For example, disc grinding should be carried out perpendicular to the weld toe. A recommendation of this report would be that additional studies be carried out to investigate the interaction of weld grinding for coating preparation and weld fatigue performance.

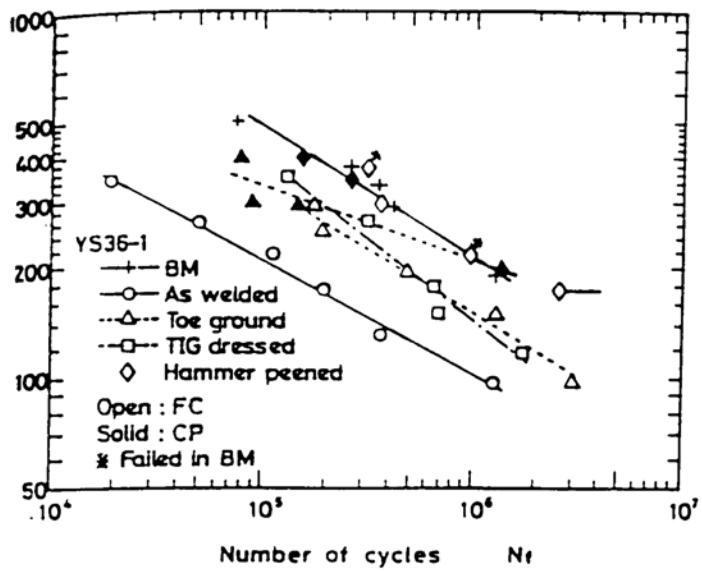


Figure 4.5 Effect of Weld Toe Treatment on the Fatigue Strength of a 272 MPa Yield Strength
Steel in Artificial Seawater (Matsumoto et al., 1989)

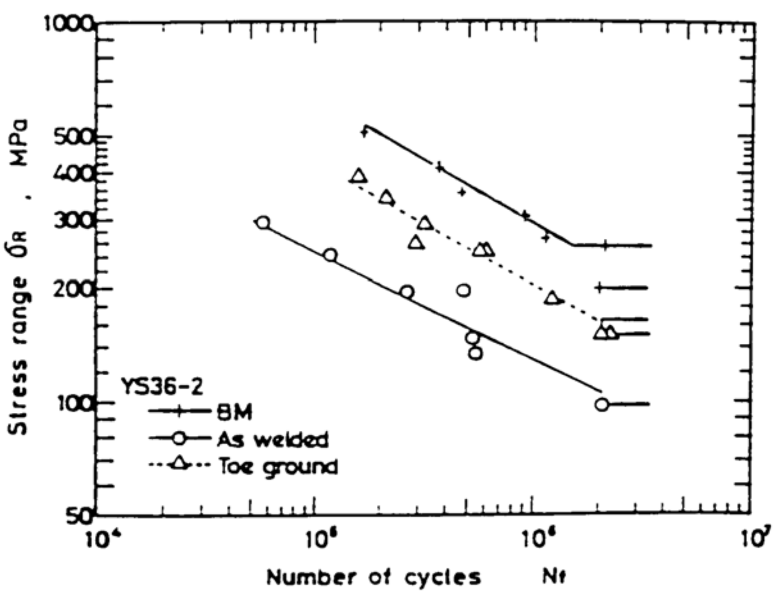


Figure 4.6 Effect of Weld Toe Treatment on the Fatigue Strength of a 465 MPa Yield Strength

Steel in Artificial Seawater (Matsumoto et al., 1989)

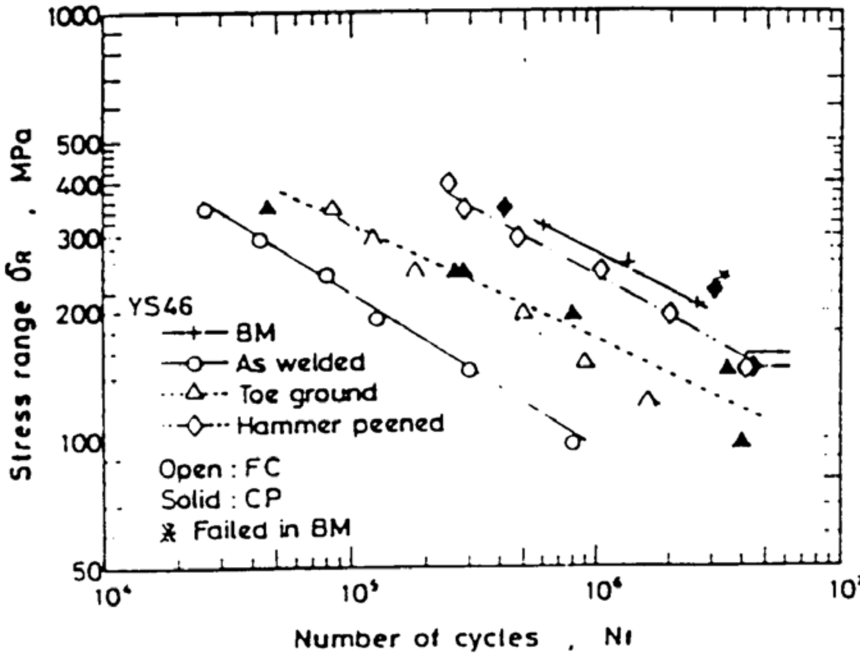


Figure 4.7 Effect of Weld Toe Treatment on the Fatigue Strength of a 481 MPa Yield Strength

Steel in Artificial Seawater (Matsumoto et al., 1989)

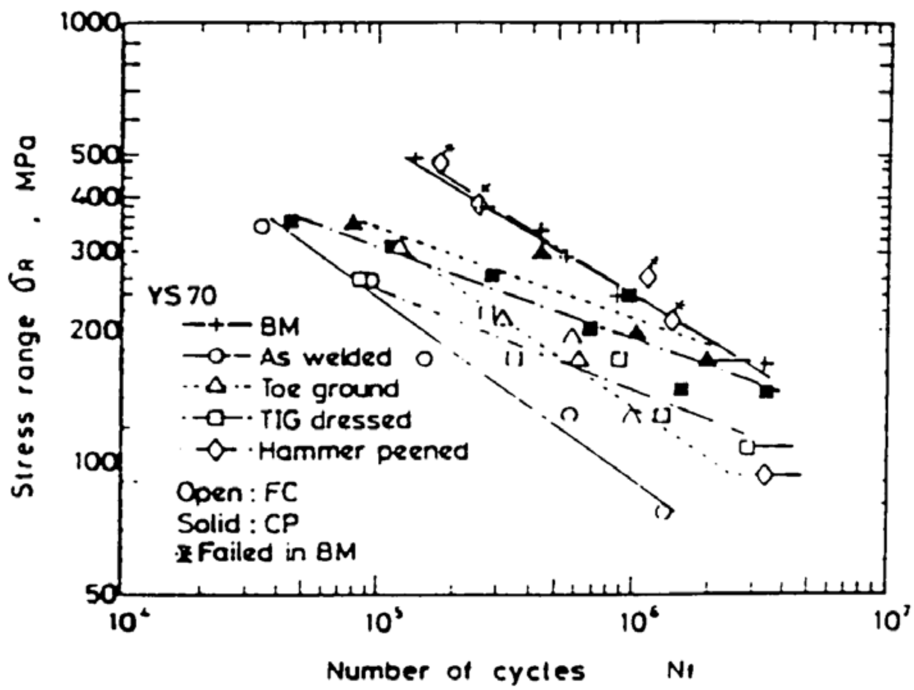
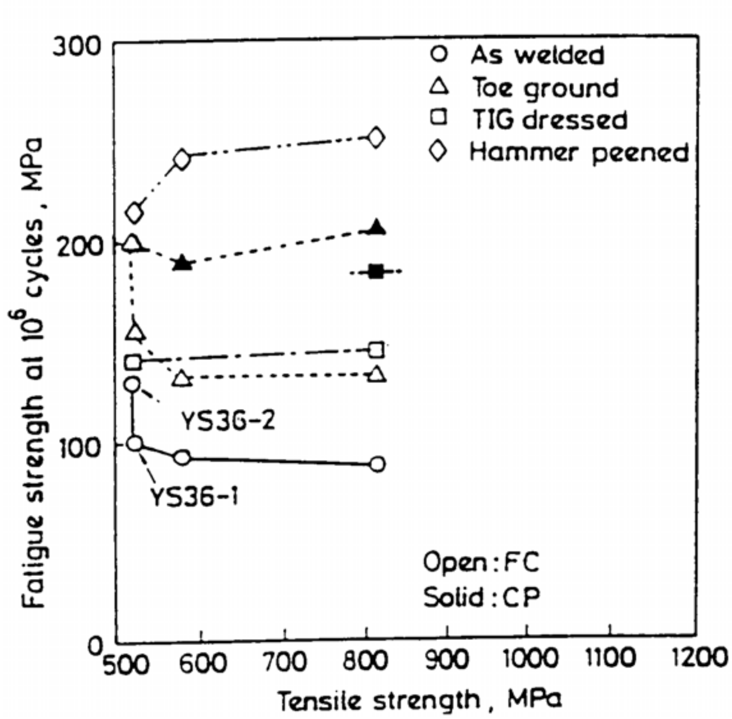


Figure 4.8 Effect of Weld Toe Treatment on the Fatigue Strength of a 764 MPa Yield Strength



in Artificial Seawater (Matsumoto et al., 1989)

Figure 4.9 Plot of the Corrosion Fatigue Strength at 10^6 Cycles vs Tensile Strength (Matsumoto,
1989)

Sacrificial anodes are pieces of less noble material, usually zinc, which corrode preferentially to the steel, thereby providing protection to the steel. Note that sacrificial anodes work only in environments where an electric potential can be developed, ie. when immersed in sea water. The use of sacrificial anodes should improve the corrosive environment to either Optimum Cathodic Protection or Cathodic Overprotection. However, in practice the systems usually result in cathodic overprotection.

In summary, burr grinding treatments should only be considered where there is adequate corrosion protection. Unprotected joints treated by toe grinding may actually perform inferior to as-welded joints in terms of fatigue strength and corrosion resistance.

4.2.4 Equipment

Weld toe burr grinding requires a high speed pneumatic, hydraulic or electric grinder with rotational speed from 1500 to 40000 rpm. The tool bit is normally a tungsten carbide burr (or rotating file) with a hemispherical head. To avoid a notch effect due to small radius grooves, the burr diameter should be in the 10 to 25 mm (3/8 to 1 in.) range for application to welded joints with plate thicknesses (t) from 10 to 50 mm (3/8 to 2 in.). The resulting root radius of the groove should be greater than 0.25 t.

4.2.5 Operator Training

Some skill is required to perform burr grinding to the specified procedures and a training program should be implemented for inexperienced operators. The program should include demonstrations of both acceptable and unacceptable ground welds, and an explanation of the factors that are important for the success of the treatment. The program should include actual grinding of at least 1 m of weld, preferably in several positions, combined with periodic inspection and evaluation.

4.2.6 Safety Aspects

The high speed grinding tool removes material at a high rate, and produces sharp hot cuttings. The process is therefore capable of inflicting serious injuries to the operator or bystanders. Mandatory protective gear includes heavy protective clothing, leather gloves, safety glasses and ear protection.

4.2.7 Weld Preparation

The weld should be de-slagged and cleaned by wire brush prior to the burr grinding treatment.

4.2.8 Burr Grinding Procedure

The burr grinding procedure is illustrated in Figure 3.3. The burr should be centred over the weld toe with the tool axis approximately 45^{o} to the main plate, and from 15 to 45^{o} to the direction of travel. The grinder can either be pulled or pushed in the travel direction, although the former is usually better suited for establishing a straight groove of even depth.

The grinding must extend to a depth of at least 0.5 mm (0.02 in.) below any visible undercuts or flaws at the weld toe as illustrated in Figure 3.2. However, the maximum depth should not exceed 5% of the plate thickness for plates up to 40 mm (1.6 in.) thickness. For thicker plates, the maximum grinding depth is 2 mm (0.08 in.).

The finished ground surface should be as smooth as possible, with any grinding marks at right angles to the line of the weld toe.

4.2.9 Inspection and Quality Control

The ground weld should be subjected to a visual and dimensional inspection of the weld toe radius and depth of grinding and to ensure that all weld toe defects and undercuts are removed. A rule and weld gage are required, as well as a low power magnifying glass of approximately 5X. A cast made of silicone rubber or other suitable material is useful for measuring the local geometry of the weld toe. The visual inspection should ensure that all traces of the original weld toe is removed. It is important that the groove should not exhibit deep scratches in the length direction; all grinding marks should be in the direction transverse to the weld.

4.2.10 Remedial Treatment

If small exposed defects remain after grinding to the maximum prescribed depth, the joint can be treated by hammer peening to prevent cracks from propagating. The peening treatment should extend to at least 20 mm (3/4 in.) outside the defect.

This remedial treatment should not be relied on for larger planar defects, more than 2 mm (0.08 in.) in surface length, located transverse to the stress direction (eg. lack of fusion or hydrogen cracks). If such defects are present, the weld should be considered defective and repaired.

4.3 TIG DRESSING

4.3.1 Applications

The TIG dressing technique may be applied for new constructions or for improving the repair life of welds. It also has some potential for linking with automatic welding equipment. As with burr grinding, the TIG dressing improvement technique is aimed at removing small crack-like defects and reducing the notch stress concentration at the weld toe. Since the improvement in fatigue strength is due to a modification in the conditions at the weld toe, the TIG dressing technique should only be considered as a treatment for weld details where failure can be expected to occur at the weld toe.

TIG dressing is most successful when applied to the following basic types of details:

a) Transversely loaded butt welds (welded from both sides); and
b) Transversely loaded full penetration T-joints and cruciform joints.
c) Longitudinally loaded weld terminations.

Due to the uncertainty about the initiation site of the fatigue crack, caution should be used when considering applying TIG dressing improvement techniques to the following types of basic welded details:

a) Longitudinally loaded butt weld (oriented parallel to the main stress direction);
b) Longitudinally loaded groove welds;
c) Longitudinally loaded fillet welds (both continuous and intermittent);
d) Transverse butt welds made from one side and those made onto permanent backing;
e) Connectors and studs;
f) Cruciform and T joints with partial penetration butt or fillet welds;

g) Coverplates; and
h) Lap joints.

If applying weld toe fatigue improvement techniques to these types of details, checks should be made to ensure that fatigue failure will not first occur at the weld root or other site in the weld detail as discussed for toe grinding in Section 4.2.1.

4.3.2 Fatigue Strength Improvement By TIG Dressing

There is less guidance, compared to toe grinding, on the degree of improvement that may be achieved by TIG dressing in the various design codes.

Lloyd's' fatigue assessment procedure (1996) suggests the amount of increase in fatigue life can be estimated to be of the order of at least 50% in the high cycle region. The Lloyd's Register (LR) procedures require that the actual quantitative improvement should be agreed upon between the designer and LR. It is intended that the level of improvement will be based upon existing relevant experimental data.

Haagensen (1996) recommends an increase of 30% in stress on the as-welded design S-N curve for all joints, with no change in slope of the curves (i.e., m=3), as a conservative lower bound. This corresponds to approximately a 120% increase in the fatigue life, provided the life of the as-welded joint is greater than 10^6 cycles. The available experimental data does not indicate a significant trend of increasing fatigue improvement with increasing tensile strength (Figure 3.9). Higher levels of fatigue strength improvement should be justified based on experimental data for similar types of joints and steels.

4.3.3 Corrosion Protection

Results reported by Haagensen (1981), Figure 4.10, show a strong influence of free corrosion on the fatigue life of TIG dressed joints however there are still significant improvement over the

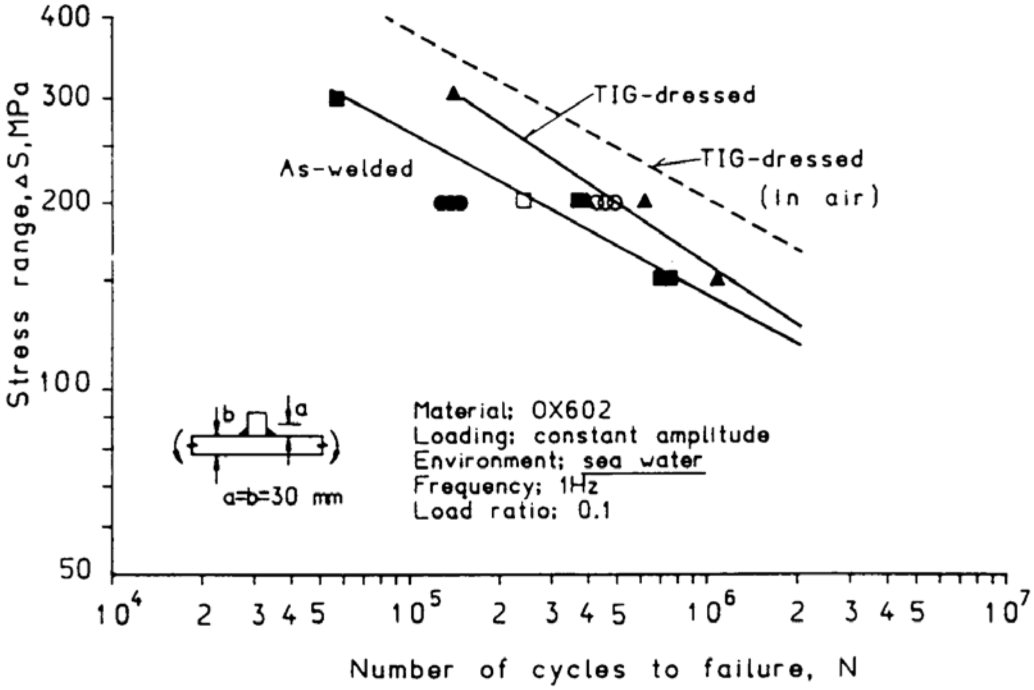


Figure 4.10 Influence of Seawater Corrosion on the Fatigue Strength of As-Welded and TIG Dressed Specimens (Haagensen, 1981)

as-welded free corrosion results. Matsumoto et al. (1989) further reported that optimum cathodic protection gave an additional improvement to the corrosion fatigue strength of the TIG dressed joint, Figures 4.5 and 4.8. This improvement in corrosion fatigue strength due to cathodically protected TIG dressed joints was 50% and 60% for the 372 and 764 MPa yield strength steel respectively.

Despite the conclusions one might make from the limited experimental results, it is recommended that a benefit in fatigue life for TIG dressed joints should only be considered where there is adequate corrosion protection. It should be assumed that unprotected joints treated by TIG dressing will perform similarly to as-welded joints in terms of fatigue strength in free corrosion. Any increase in fatigue strength of TIG dressed joints in free corrosion must be justified by experiment for the particular application and corrosive environment.

4.3.4 Equipment

A standard TIG welding machine is required. Equipment with large capacity is preferred since this helps stabilize the dressing operation by increasing the heat input, and improves dressing speed. Argon is normally used as shielding gas. Additions of helium is beneficial as this gives a larger pool of melted metal due to a larger heat input. Table 4.1 summarizes typical conditions and range of dressing parameters.

Table 4.1 Typical TIG Dressing Conditions

Shielding Gas	Argon
Gas Flow Rate	7-12 litre/min
Nozzle Diameter	10-14 mm
Preheat[1]	50-200 ^oC
Electrode Diameter	3.2 or 4.0 mm
Voltage, V	12-17 volts
Current, A	160-250 amp
Dressing Speed, S	80-160 mm/min
Heat Input, HI[2]	0.5-2.5 kJ/mm

[1] Dependant on steel type and plate thickness

[2] Heat Input is calculated from $HI = (60 \cdot V \cdot A) / (1000 \cdot S)$

4.3.5 Operator Training

TIG dressing requires a relatively high level of operator skill and it is recommended that a trial program be set up to familiarize the welder with the technique and develop optimum dressing conditions, similar to other welding process qualification programs. The program should include demonstrations of both acceptable and unacceptable dressed welds, and an explanation of the factors that are important for the success of the treatment. The trials should include practice dressing with different heat inputs and torch positions, as well as arc starting and stopping techniques. The program should be supplemented by periodic inspection and evaluation.

4.3.6 Safety Aspects

Standard welder safety equipment is mandatory.

4.3.7 Weld Preparation

TIG dressing is sensitive to weld contaminants, much more so than other weld improvement methods. As a result, the weld and adjacent plate should be thoroughly de-slagged and wire brushed to remove all traces of mill scale, rust, oil and paint. If necessary, light grinding should be used to obtain a clean surface.

4.3.8 TIG Dressing Procedure

Preheat

The heat input during TIG dressing is normally less than that used for welding the joint. Therefore, as a rule the minimum preheat temperature to be used should be equal to or larger than that specified in the welding procedure. The exception to this is welds produced by the Flux Cored Arc Welding (FCAW) process for which the risk of weld metal cracking is reduced (due to reduced hydrogen content), which means that the preheat temperature for TIG dressing can be reduced. The preheat temperature for TIG dressing of FCAW joints may be chosen on the basis of the preheat temperature that would be used for MMA welding of the joint.

Dressing Parameters

Suitable dressing conditions for the horizontal downhand position are shown in Figure 4.11. Dressing conditions may vary with the welding position. As a general rule a high heat input should be used since this gives a low hardness in the HAZ. However, an excessive heat input caused by a combination of high current and low travel speed can result in undercuts or a substandard bead profile.

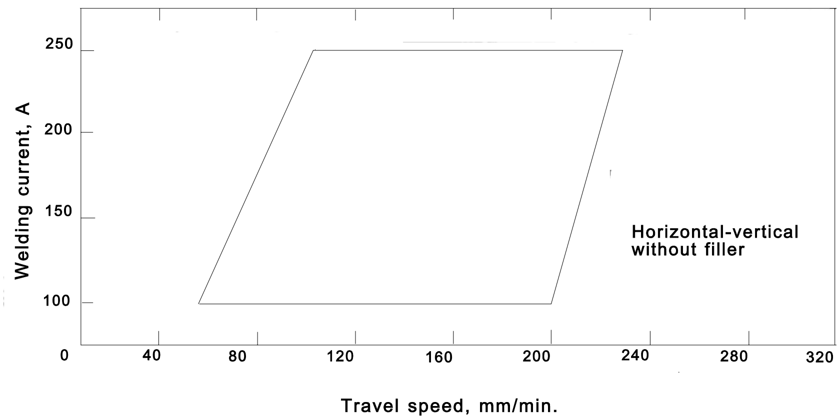


Figure 4.11 TIG Dressing Conditions (Millington, 1973)

Positioning of Torch and Bead Profile

Optimum torch positioning and bead profiles are illustrated in Figures 3.6 and 3.7. Normally the best result is obtained when the arc centre is a small distance (0.5 - 1.5 mm) outside the weld toe. If the arc is positioned too close, the weld bead may result in formation of a new toe as shown in Figure 3.7 (b) and (c). Remedial treatment should be considered in such cases. A remelted weld toe as shown in Figure 3.7 (a) represents an optimum shape with respect to fatigue improvement.

Arc Stopping and Restarting

Arc stopping and restarting may create craters or poor bead profiles. This can be avoided by starting the arc about 6 mm behind the stop position as indicated in Figure 4.12 (a). Other acceptable methods involving starting or stopping from the weld bead are also illustrated in this figure.

4.3.9 Inspection and Quality Control

In the case of TIG dressing the quality of the treatment is so dependent on the combination of the dressing parameters and the skill of the operator that it is recommended that a qualification test be carried out to familiarize the welder with the technique and to develop optimum dressing conditions.

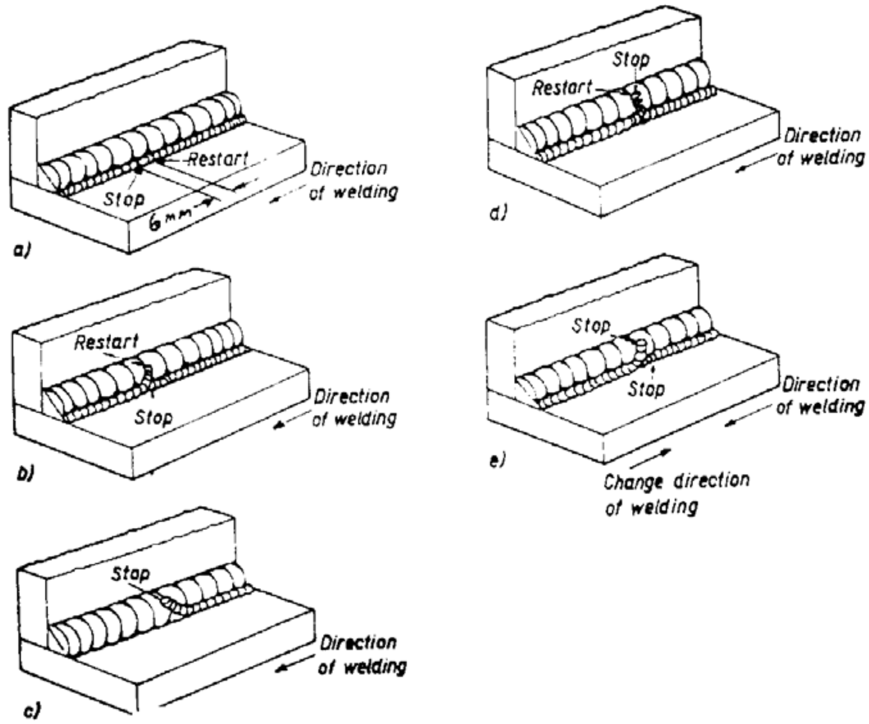


Figure 4.12 TIG Dressing Stop and Restart Techniques (Haagensen and Maddox, 1995)

Inspection is carried out visually to ensure that an optimum shape of weld toe and a large radius transition from the weld metal to the base plate is obtained as shown in Figure 3.7.

4.3.10 Remedial Treatment

In the case of weld toe shapes which are less than optimum, remedial action can be taken by performing a new dressing run. The ease of repeating TIG dressing is one of the advantages of this method.

4.4 HAMMER PEENING

4.4.1 Applications

The hammer peening technique may be applied for new constructions or for improving the repair life of welds, however it is particularly effective for the latter. Hammer peening introduces large residual compressive stresses (up to the yield strength) which can penetrate deep into the plate thickness, up to 6 mm (0.25 in.). In the case where surface cracks are repaired by grinding and welding, it can sometimes occur that the crack tips are not fully removed. In such cases, cracks will re-initiate and propagate relatively soon after the repair is completed. By applying a hammer peening treatment, the crack tips that are missed in the original repair will be exposed to the residual compressive stress field induced by the treatment. This can impede the cracks from re-initiating and therefore greatly extend the repair life.

Hammer peening treatments have been used with success for repairing side shell longitudinal / web frame connections on TAPS tankers, similar to the detail shown at the bottom of Figure 2.2 (Lacey, 1996). These particular details experienced chronic cracking which proved to be very expensive to repair each year. To remedy the problem, the design of the connections in the tanks at midships were modified, while hammer peening treatments were applied to the brackets elsewhere. The cost of hammer peening a joint was estimated to be approximately ten times less costly than the modified design. To date, it has been reported that the connections that were hammer peened have not experienced any cracking after three years (where previously cracks were occurring every year). It was also reported that a few of the modified brackets have since experienced cracks. This example, therefore, suggests that hammer peening treatments can be a very cost-effective method of improving the fatigue strength of details that have experienced cracking problems.

Details which can be readily considered for hammer peening include:

a) Transversely loaded butt welds (welded from both sides); and
b) Transversely loaded full penetration T-joints and cruciform joints.
c) Longitudinally loaded weld terminations.

Due to the uncertainty about the initiation site of the fatigue crack, caution should be used when considering applying hammer peening improvement techniques to the following types of basic welded details:

a) Longitudinally loaded butt weld (oriented parallel to the main stress direction);
b) Longitudinally loaded groove welds;
c) Longitudinally loaded fillet welds (both continuous and intermittent);
d) Transverse butt welds made from one side and those made onto permanent backing;
e) Connectors and studs;
f) Cruciform and T joints with partial penetration butt or fillet welds;
g) Coverplates; and
h) Lap joints.

If applying weld toe fatigue improvement techniques to these types of details, checks should be made to ensure that fatigue failure will not first occur at the weld root or other site in the weld detail as discussed for toe grinding in Section 4.2.1. It should be noted that the TAPS tanker detail discussed above, was in fact a lap joint.

4.4.2 Fatigue Strength Improvement By Hammer Peening

There is very little guidance on the degree of improvement that may be achieved by hammer peening in the various design codes. The IIW/IIS proposition for joints improved by hammer peening (Maddox, 1993) is to reclassify all treated joints as

Eurocode 3 Class 125 joints, which is approximately equivalent to the Class A curve given in Figure 2.9. However, the stress range to be used in the fatigue assessment is to be redefined as:

$\Delta\sigma' = \sigma_{max}$ for $R \geq 0$

$\Delta\sigma' = \Delta\sigma$ for $R<0$

where $\Delta\sigma = \sigma_{max} - \sigma_{min}$

σ_{max} = maximum nominal value of applied stress in the cycle;

σ_{min} = minimum nominal value of applied stress in the cycle;

$R = \sigma_{min} / \sigma_{max}$ is the applied stress ratio.

Alternatively, Haagensen (1996) recommends an increase of 60% in stress on the as-welded design S-N curve for all joints, with no change in slope of the curves (ie. m=3), as a conservative lower bound.

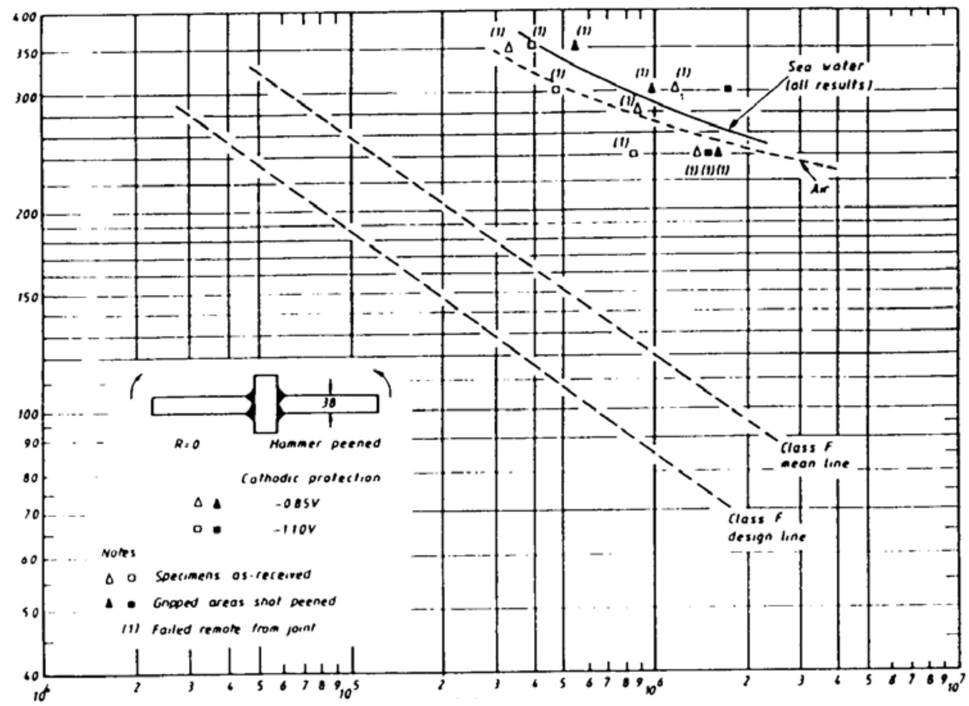
Neither of these approaches take into account the increase in fatigue strength with increasing tensile strength that the experimental data suggests for hammer peening treatments (Vosikovsky, 1992). Nor do they appear to account for the shift and rotation of the S-N curve for welds improved by hammer peening. The effectiveness of this improvement method is greatest in the high cycle / low stress part of the S-N curve. In the low cycle / high stress region, the effect of most improvement techniques is small or non existent. Thus it appears that further research and development is required to establish appropriate fatigue S-N curves for hammer peening treatments of different types of detail in different steels. In the meantime, the above recommendations may be used as conservative guidelines. Higher levels of fatigue strength improvement should be justified based on experimental data for similar types of joints and steels.

It should be noted that Lloyd's' fatigue assessment procedure (1996) indicates that stress relief improvement methods are not adequate for improving the fatigue strength of ship structural details since residual stresses may be relaxed if peak service loads cause local yielding. The discussion is, however, ambiguous for it is not clear whether they are referring to hammer peening treatments or to thermal (or other types) of weld stress relief. There does not appear to be any experimental evidence indicating that the effectiveness of the hammer peening treatment is reduced as a result of periodic overloads. Indeed, as discussed in section 4.4.1, hammer peening treatments have been used quite successfully in ship structure welded joints subjected to variable amplitude loading.

4.4.3 Corrosion Protection

The effect of seawater on the performance of hammer peening can be assessed by results presented by Booth (1987), Figure 4.13, for cruciform joints tested in artificial seawater with optimum cathodic protection and also with cathodic overprotection. These results showed that the fatigue performance in seawater using cathodic protection, (optimum and overprotection) were at in-air levels and that the fatigue strength under these conditions was increased to a level comparable with the parent plate.

Stress Range, N/mm^2



Cycles

Figure 4.13 The Effect of Seawater Corrosion on Hammer Peened Specimens (Booth, 1987)

Matsumoto et al. (1989) also presents results for hammer peened joints tested under free corrosion and cathodic protection conditions as shown in Figures 4.5, 4.7 and 4.8. They also conclude that hammer peening was the most promising weld toe treatment for increasing corrosion strength.

In summary, while hammer peening treatments appear to be less influenced by corrosion than other treatments, it is still recommended that they only be considered where there is adequate corrosion protection. As was the case with the in-air results hammer peening gives the greatest improvement in corrosion fatigue behaviour of all the improvement techniques considered, when combined with optimum cathodic protection. In this case the fatigue strength is increased to a level which is comparable to the base metal. However, unprotected joints treated by hammer peening should not be relied on to perform better than as-welded joints in terms of fatigue strength and corrosion resistance.

4.4.4 Equipment

A pneumatic, hydraulic or electric hammer is required. Conventional chipping hammer equipment may be used. A suitable pneumatic hammer gun has a 40 mm diameter piston, operates at an air pressure of 5 to 7 bars, and delivers 30 to 40 blows per second. A suitable electric hammer is a rotary hammer which has a 700 W motor and delivers about 50 blow per second. However, more modern equipment is now becoming available which is lighter, vibration dampened and silenced. These features increase operator comfort and ease of use, and should improve control of the hammer peening operation.

Hardened steel tool bits with approximately hemispherical tips, 6 to 18 mm in diameter, and 150 to 250 mm in length are used. Such tools are not generally available as standard off-the-shelf equipment, but can be easily produced by grinding the tips of standard chisels.

4.4.5 Operator Training

Some skill is required to perform hammer peening to the specified procedures and a training program should be implemented for inexperienced operators. The program should include demonstrations of both acceptable and unacceptable peened welds, and an explanation of the factors that are important for the success of the treatment. The program should include peening of at least 1 m of weld, preferably in several positions, combined with periodic inspection and evaluation.

4.4.6 Safety Aspects

Hammer peening, even with modern silenced units, is an extremely noisy operation so that it is essential that the operator and others working in the vicinity use ear protection. Normal protective clothing for working in a fabrication shop is adequate, but it should include safety goggles or a face mask.

4.4.7 Weld Preparation

The weld should be de-slagged and cleaned by wire brush to remove scale and oxide layer prior to the peening treatment.

4.4.8 Hammer Peening Procedure

The hammer peening procedure is illustrated in Figure 3.17. Effective treatment requires reasonably accurate positioning of the tool over the weld toe so that metal on each side (both weld and parent plate) is deformed. The resulting groove must be smooth and free from obvious individual indentations. Repeated peening, usually four passes, is required to achieve full coverage and a smooth surface.

4.4.9 Inspection and Quality Control

The quality control of the hammer peening treatment also requires operator training to ensure that the treatment of weld joints is reliable and repeatable. In general it is not possible to verify that hammer peening has been carried out correctly by visual inspection alone. Many of the important features such as coverage and surface finish can only be described qualitatively, while the extent of the plastic deformation, which reflects the level of compressive stresses is too small for reliable measurement. Therefore, the most practical quality control strategy is to establish an acceptable hammer peening procedure and then to ensure that it is followed carefully.

The treatment of an actual weld area can be verified visually and the weld surface compared with photographs of reference peened welds, a library of which would have to be developed. The indentation along the weld toe should be uniform with a smooth surface finish. As a guide, the indentation depth should vary between about 0.5 mm in mild steel (yield strength up to 250 MPa) to 0.25 mm in higher strength steels (250 to 450 MPa). The indentation depth should normally not exceed 1 mm. Upon visual inspection, if the above deformation criteria is not obtained, the number of peening passes should be increased until the proper weld toe deformation is produced. However, care should also be taken to ensure that an area is not over-peened which would be illustrated by weld metal which is folded over the weld toe or cracks in the deformed material. If such defects are present, the weld should be considered defect and repaired. Assuming there are no planar defects, a possible remedial action would be rewelding and grinding.

4.5 PRACTICAL TESTS OF WELD FATIGUE IMPROVEMENT TECHNIQUES

In order to provide a further assessment of the practical implementation of the three weld improvement methods on typical ship weld assemblies, a series of tests were conducted. The objective of these tests was to apply the three techniques (burr grinding, TIG dressing and hammer peening) under similar conditions in order to collect data relating these techniques to pertinent shipyard production criteria. These tests were performed in the laboratories of the MIL Davie shipyard in Lauzon, Quebec.

4.5.1 Procedure

Six assemblies (T) with a scallop in the middle were welded using the FCAW (flux cored arc welding) process. The joint specimen used in the assessment tests is shown in Figure 4.14. A fillet weld with an 8-mm leg was made in a single weld pass (see welding parameters on Figure 4.14). Weld flux was removed by brushing, the welds being left as is for subsequent operations.

The weld assemblies were installed in three positions: horizontal, vertical and overhead (see Figure 4.15). This is to simulate the real working environment in newly-built or existing ships. Figures 4.16 to 4.18 show the three different techniques being applied to horizontally-positioned assemblies. Each technique was used on the weld toe of the fillet welds on their entire length, including wraps at the ends of the assemblies and inside the scallop. The equipment and methods used for all the tests were applied in accordance with the IIW specifications by Haagensen and Maddox (1995), as summarized in sections 4.2 to 4.4. Weld improvement data sheets for the tests based on these procedures are included in Appendix A, B and C for burr grinding, TIG dressing and hammer peening respectively.

The MIL Group Inc. R & D Centre Welding and Metallurgy	WELDING DATA SHEET	REPORT No.: S155

Base Material: CSA G40.21M, Grade 300W

FILLER MATERIAL:
- Trade Name: LAT-91
- Class: CSA W48.5M, class E4801T-9CH
- Diameter: 1.2 mm

Flux: N/A

Gas: 75% Ar/25% CO_2 Gas Flow: 18-20 l/min.

Backing: N/A

Welding Process: FCAW / Semi-auto.

Arc Characteristics: DC / Reverse polarity

Welding Position: Horizontal (2F)

Electrode Stick Out: 19 mm + tip recess of 3 mm

Pre-Heating Temperature: Room temperature

Interpass Temperature: N/A (one pass only)

Weld Bead Length: -

Date: August 20, 1996

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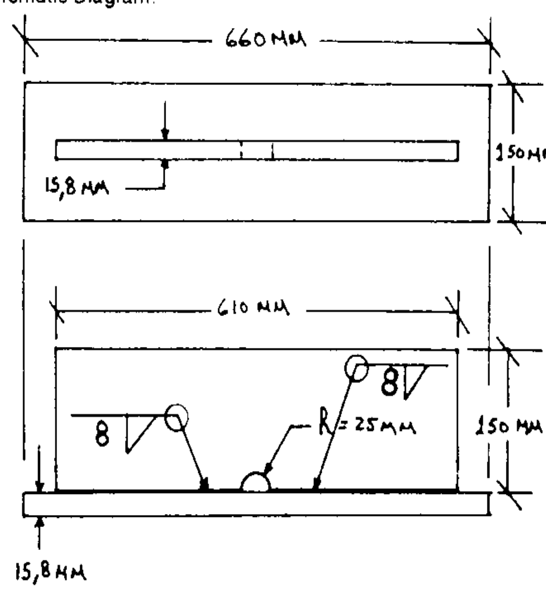
Mother Plate ID: -

Ass. Plates ID: -

Ass. Dim.: As per sch. diagram

Schematic Diagram:



Note: Welding of six (6) assemblies.

Side	Layer no	Pass no	Current Set (A)	Current Read (A)	Voltage Set (V)	Voltage Read (V)	Wire Feed Speed (m/min)	Arc Travel Speed (mm/min)	Energy (J/mm)
		1		230		24.5	6.9	231	1465

Figure 4.14 Specimen Used for Evaluating Practicality of Fatigue Improvement Techniques

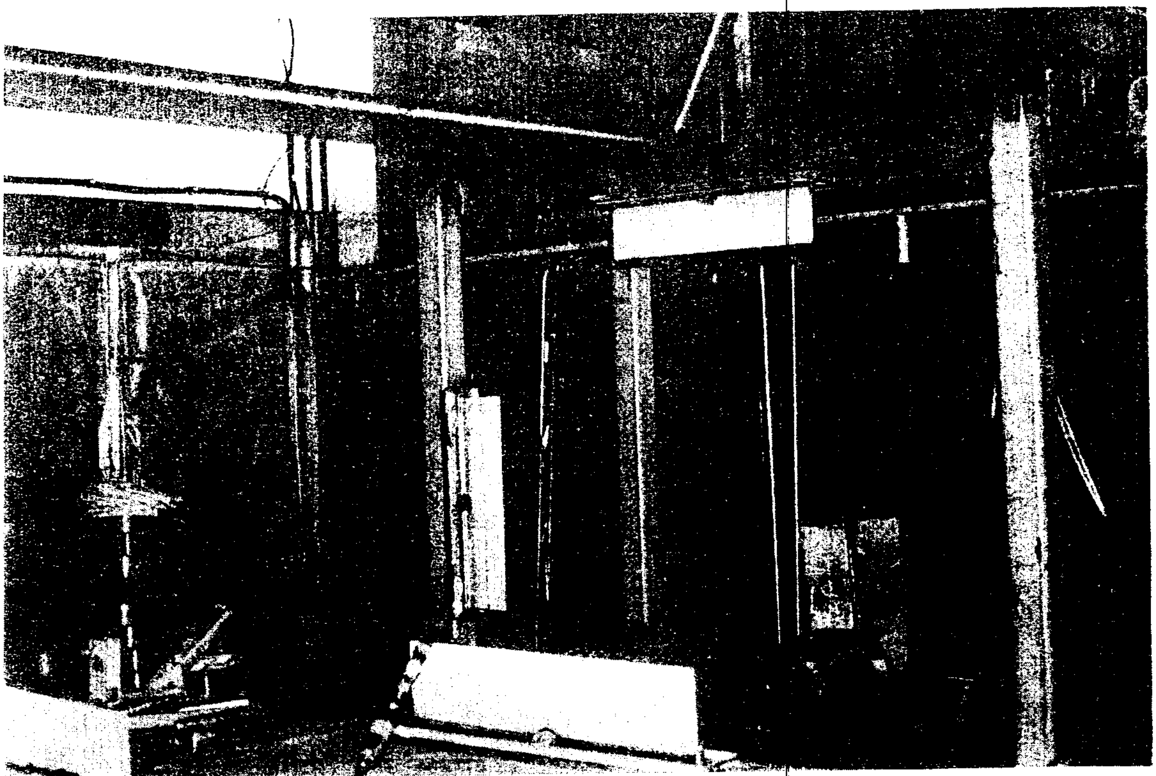


Figure 4.15 Three Positions of Specimen Setup

Figure 4.16 Burr Grinding Technique Being Applied to a Horizontally-Positioned Specimen

Figure 4.17 TIG Dressing Technique Being Applied to a Horizontally-Positioned Specimen

Figure 4.18 Hammer Peening Technique Being Applied to a Horizontally-Positioned Specimen

Figure 4.18 Hammer Peening Technique Being Applied to a Horizontally-Positioned Specimen

4.5.2 Test Results

All the parameters of the improvement methods were recorded, for each position, on the data sheets included in the appendices of this report. Also included are a macrographic evaluation of the weld bead after improvement of the weld toes as well as the results of hardness measures taken in the heat affected zone by TIG dressing. The following observations were made:

1. The time spent in applying the improvement methods depends directly on the profile of the weld bead. In case of profiles where the overlap of the weld is important, the time required to make the profile smoother is rather longer, particularly for burr grinding and hammer peening. On the other hand, the time devoted to TIG dressing is less influenced by this phenomenon since the material is fused by the electric arc.

2. The work angles of the three improvement methods change inevitably for the wraps at the ends of the assemblies and the scallop which results, among other things, in making the work time longer in those locations.

3. The pressure put on the tool affects the work time for burr grinding and hammer peening. The pressure exerted on the tool may vary from one worker to another.

4. Compared to TIG dressing, the ease and therefore the speed for installing the burr grinding and hammer peening equipment is clearly superior.

5. The conical tip of the burr grinding tool was changed for each position in order to recreate the same conditions for each assembly. As for hammer peening, the tip was ground to an initial diameter of 9 mm and there was only one subsequent grinding for the three tests.

6. The length of the treatment is not based on the length of the weld but rather on the length of its toes (2 x length of weld).

7. The average travel speed of the tool and the arc for the three improvement methods are summarized in Table 4.2. It was determined that burr grinding of an 8 mm (0.315 in.) fillet weld is the least costly technique at 0.10 hours/metre. TIG dressing is moderately more expensive at 0.13 hr/m, and four-pass hammer peening required 0.20 hr/m. These may be used for estimating baseline labour costs for applying the three techniques to similar types of details.

8. The practical tests were performed under conditions where access to the weld beads was good. This will not always be the case in production, in the blocks in the shops, or in the ships. Operation factors should be applied to the baseline costs to take into account the accessibility to the weld beads and the work locations. The operation factors presented in Table 4.3 are based on the experience of the MIL

Davie shipyard. These may be used as a guide for establishing cost estimates for application of the improvement techniques in different work locations and levels of accessibility.

9. Some hardness values in the heat affected zone during TIG dressing exceed 300 HV. This hardness level is representative of results obtained on steels more sensitive to the change of the microstructure and high cooling rates than the 300 W grade steel used in the test specimens (for example, steels of higher carbon equivalent, or quench and tempered, or HSLA steels).

Table 4.2 Baseline Cost Factors For Application of Improvement Techniques

Method	Application Speed (mm/min) for Position			
	Flat	Vertical	Overhead	Average
Burr grinding	182	131	175	162.7
Hammer peening	69	87	91	82.3
TIG Dressing	127	122	134	127.7

Notes:
1) The average speed is the average value of the three speeds measured, that is one per welding position.
2) The time measured is of course based on an operation factor of 100%.

Table 4.3 Operation Factors for Costs of Improvement Techniques

Location	Access	Operation factor (%)
General	Easy	50
Shop	Difficult	35
Erection	Difficult	25

4.5.3 Conclusions and Recommendations From Tests

1. Burr grinding, hammer peening and TIG dressing are three weld toe improvement methods easily used in all positions provided there is good access to the weld bead. Operator qualification and experience is not too demanding for the application of burr grinding or hammer peening. On the other hand, some welder qualification and experience are important for TIG dressing.

2. Welder qualification for TIG dressing could be the same as the qualification required in the welding standards; that is a welder qualified for all positions (6G) with the GTAW process according to the type of material to be welded. This would ensure a quality of work above a minimum level.
3. The minimum operator experience for burr grinding and hammer peening could be less than 10 hours, including training and practice on 1 metre of weld.
4. A visual inspection of the entire length of the improved welds as well as the use of a rule and a weld gauge is recommended. In most cases this will ensure adequate quality provided the operator has been properly trained and is experienced in the technique.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Fatigue cracking often occurs at welded details in ship structures. This report has reviewed the physical mechanisms which result in the fatigue performance of welded details being much reduced in comparison to plain steel plate The general approaches which may be used to improve the fatigue performance of fatigue critical weld details in ships was also briefly outlined, including improvements in the design, fabrication and maintenance procedures.

A comprehensive review of the various techniques that improve the fatigue strength of the weld itself was presented. The review covered machining techniques, weld remelting techniques, peening methods, residual stress relief techniques, special welding techniques, and overloading techniques. Comparisons of the relative fatigue improvement performance, costs, advantages and disadvantages of the various techniques were made.

Of the various techniques, weld grinding, weld profiling, TIG dressing and hammer peening appear to hold the best potential for ship structure applications. Each of these techniques provide a significant and repeatable improvement in fatigue strength and involve equipment and procedures that are familiar to shipyards.

Stress relief techniques including PWHT, vibratory stress relief, Gunnert's method and explosive treatments do not appear to be practical for ship applications. For these techniques, the fatigue strength improvement benefit is minimal and / or the procedures involved are simply not possible in a shipyard environment.

Other techniques including spot heating and local compression may hold some potential as treatments for specific repair applications.

Detailed guidance on the application of the burr grinding, TIG dressing and hammer peening treatments for application to ship structures has been presented. The guidance covers the types of applications and details that the treatments can be applied to, the degree of fatigue strength or life improvement that can be achieved, corrosion protection considerations, and optimal procedures for application of the techniques.

The procedures for burr grinding, TIG dressing and hammer peening were tested on a representative ship detail to determine the practical issues and costs associated with each technique in a shipyard environment. It was determined that each of these techniques may be readily used in all positions as long as there is good access to the weld bead. Operator qualification and experience is not too demanding for the application of burr grinding or hammer peening. On the other hand, some welder qualification and good experience are important for TIG dressing.

The costs of applying these techniques, in terms of hours per meter weld treated, were estimated from these tests. It was determined that burr grinding of an 8 mm (0.315 in.) fillet weld is the least costly technique at 0.10 hours/metre. TIG dressing is moderately more expensive at 0.13 hr/m, and four-pass hammer peening required 0.20 hr/m. Operational factors have been presented which will allow cost estimates to be made for various work locations and accessability levels.

The acceptance of fatigue improvement techniques by designers and practising engineers is closely related to the level of quality control on the application of the treatments and the ability to ensure that the performance of the improvement technique is as claimed. Many techniques are not used because inspection and quality control are extremely difficult. Some methods, such as shot peening and toe grinding are widely used in certain industries because well developed quality control procedures exist. Without increased assurance that treatments have been properly applied and that the claimed improvement is achieved, many of the techniques will not gain acceptance in general practice.

At present there is a lack of universally accepted design S-N curves for improved joints. The guidance for allowable improvements in fatigue strength in design codes is relatively conservative and limited and, in some cases in contradiction to experimental data. Some progress is being made by the IIW Commission XIII Working Group 2 test program, the results of which should be available in the near future.

It is recommended that the following levels of improvement be used as conservative lower bounds :

- For toe grinding and TIG dressing treatments an increase of 30% in stress on the as-welded design S-N curve for all joints with no change in slope of the S-N curves (ie. m=3). This corresponds to an increase of approximately 120% in terms of fatigue life, provided the initial fatigue life of the unimproved joint is greater than 10^6 cycles.

- For hammer peening an increase of 60% in stress on the as-welded design S-N curve for all joints with no change in slope of the S-N curves (ie. m=3). This corresponds to an increase of approximately 300% in terms of fatigue life, provided the initial fatigue life of the unimproved joint is greater than 10^6 cycles.

Higher levels of fatigue strength or life improvement should be justified based on experimental data for similar types of joints and steels.

In summary, burr grinding, TIG dressing and hammer peening offer cost effective treatments for improving the fatigue strength of welded joints in ship structures. However it is suggested that they should be considered primarily as remedial actions or treatments used in repair situations rather than procedures specified in the design of new structures. They are not a substitute for bad design or workmanship. At the design stage these treatments should only be considered if the designer cannot modify the joint in question to achieve the desired fatigue performance for the overall structure.

5.2 RECOMMENDATIONS

In the previous section, some conservative guidelines were presented in regard to the increase in fatigue strength that can be achieved on application of selected weld detail fatigue life improvement techniques. Considerably more data is required to provide comprehensive systematic guidelines that designers and fabricators can use with confidence, i.e.:

1. A key recommendation of this study is to perform systematic fatigue tests on standard details to which fatigue life improvement techniques have been applied. This will allow S-N curves to be developed which can then be used alongside "standard" S-N curves.

2. As noted above, the primary application of fatigue life improvement techniques is in remedial action, or treatments, in repair situations rather than in new construction. Hence, associated with the application of these techniques, guidance is required for selection of the appropriate technique to be applied. These should be integrated, and should be consistent, with existing repair procedures, quality control and welder qualification procedures. Several of the latter may require modification and / or enhancement to accommodate fatigue life improvement techniques as normal shipyard practice.

3. In order to assess the cost-effectiveness of weld improvement techniques, shipyards need to develop associated cost data. These can then be used to conduct trade-off studies to determine if weld improvement can be substituted for reinforcing, or otherwise strengthening, a particular detail in a cost-effective manner.

In addition to the broad recommendations made above, the following, more specific, recommendations are made:

4. The preparation of weld details for the application of fatigue life improvement techniques, if not properly performed, can itself be detrimental to fatigue performance. A particular concern is the interaction of weld grinding for coating preparation and weld fatigue performance. This subject requires study.

5. The interaction between corrosion, and corrosion protection systems in weld details that have been subject to fatigue life improvement techniques, should be investigated.

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APPENDIX A

PRODUCTION DATA SHEETS FOR WELD FATIGUE IMPROVEMENT BY BURR GRINDING

THE MIL GROUP INC.
22 George D. Davie (P.O. Box 130)
Lévis (Québec) G6V 6N7
Phone (418) 837-5941

WELD TOE IMPROVEMENT BY BURR GRINDING

DATA SHEET

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W
Filler material: CSA W48.5M, Class E4801T-9CH
Welding procedure no.: S155

Identification: 2FBG7
Operator Experience: Less than 10 hrs
Training program: Less than 1 meter

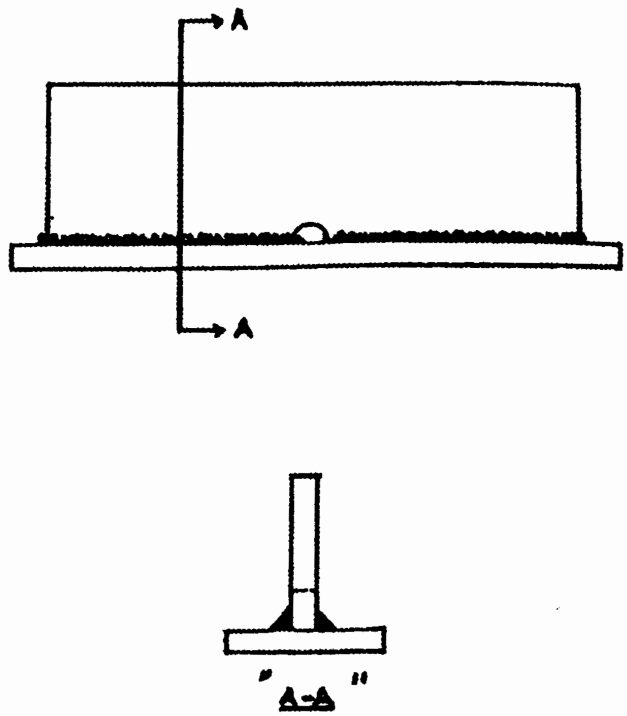
EQUIPMENT

Type: Pneumatic - UG 25NSA
Power: Air driven
Diameter tip: 12 mm (type F/SF-5)
Weight (with tip): 0.72 kg
Rotation speed: 25,000 rpm

DATA

Position: Horizontal (2F)
Work angle: 45°
Deplacement angle: Backhand 30° - 45°
Travel speed: 182 mm/mn (10.92 metre/hour)
Nbr of passes: 3 (first side) and 2 (second side)
Length of treatment: 1260 mm
Time of treatment: 415 sec.
Change of tool: New tip (type F/SF-5)
Time: –
Cause: –

SCHEMATIC DIAGRAM



INSPECTION

■ Visual ■ Dimensional

Equipment: Rule and weld gauge

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	2.00	1.50	2.50
Groove depth (mm):	0.50	0.25	1.00

Macrographic report: M97

REMARKS

1. Backward and forward motion.
2. Removal of metal more accentuated on wraps.

Operator: Christian Fortier (6062)

Date: August 28, 1996

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The MIL Group Inc.
WELDING AND METALLURGY
R&D CENTRE

MACROGRAPHIC EVALUATION

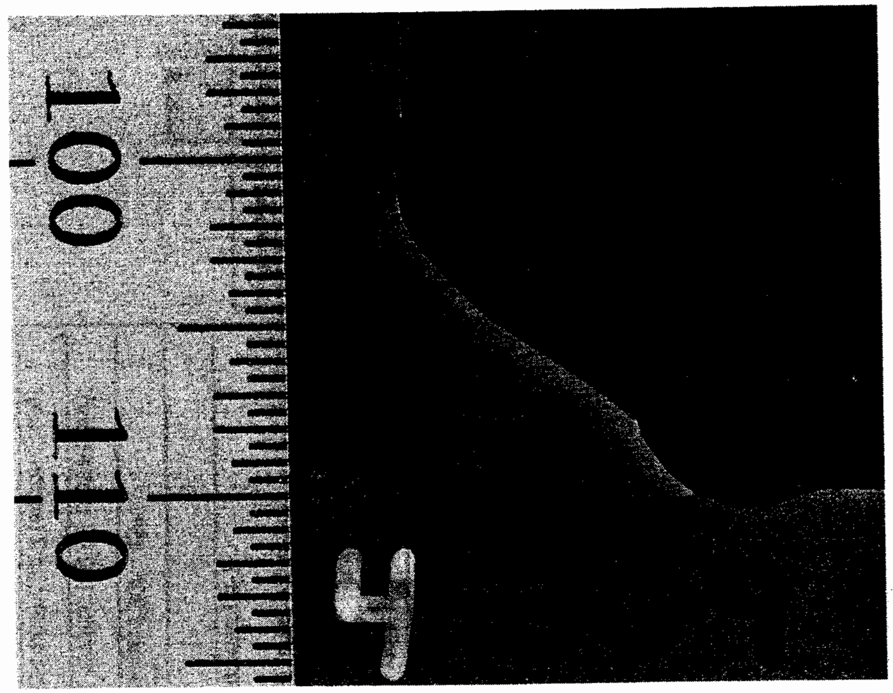
REPORT No.: M-99

STANDARD: ASTM E-340
BASE METAL: 300W
FILLER MATERIAL: LA-T-91

WELDING ASSEMBLY #: S155
ETCHANT/TIME OF ETCHING: Nital 10%/10 sec.
TEST TEMPERATURE: 20°C

DATE: August 28, 1996
MOTHER PLATE ID: —
ASSEMBLY PLATES ID: 4FBG9

SPECIMEN ID	NUMBER OF DEFECTS			TYPE, SIZE AND ORIENTATION OF DEFECTS
	BASE METAL	FILLER METAL	FUSION LINE	
4FBG9				



REMARKS: OVERHEAD POSITION

Christian Fortier (6062)
SIGNATURE
August 28, 1996
DATE

SIGNATURE
DATE

File B:\ME0097

THE MIL GROUP INC.
22 George D. Davie (P.O. Box 130)
Lévis (Québec) G6V 6N7
Phone (418) 837-5941

WELD TOE IMPROVEMENT BY BURR GRINDING

DATA SHEET

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W

Filler material: CSA W48.5M, Class E4801T-9CH

Welding procedure no.: S155

Identification: 3FBG8

Operator Experience: Less than 10 hrs

Training program: Less than 1 meter

EQUIPMENT

Type: Pneumatic - UG 25NSA

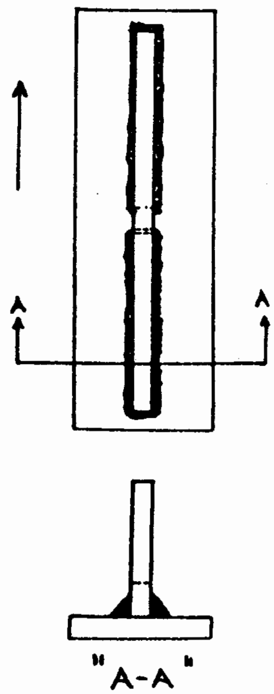
Power: Air driven

Diameter tip: 12 mm (type F/SF-5)

Weight (with tip): 0.72 kg

Rotation speed: 25,000 rpm

SCHEMATIC DIAGRAM



DATA

Position: Vertical upward

Work angle: 45°

Deplacement angle: Backhand 30° - 45°

Travel speed: 131 mm/mn (7.86 metre/hour)

Nbr of passes: 4 (first side) and 2 (second side)

Length of treatment 1240 mm

Time of treatment 566 sec.

Change of tool: New tip (type F/SF-5)

Time: --

Cause: --

INSPECTION

■ Visual ■ Dimensional

Equipment Rule and weld gauge

REMARKS

1. Upward and downward motion.
2. Removal of metal more accentuated on wraps.

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	2.50	2.00	3.00
Groove depth (mm):	0.50	0.25	1.00

Macrographic report M98

Operator: Christian Fortier (6062)

Date: August 28, 1996

File C\1996\INGPROD CF\TABLEAU\WTIBG\BG0001

THE MIL GROUP INC. 22 George D. Davie (P.O. Box 130) Lévis (Québec) G6V 6N7 Phone (418) 837-5941	WELD TOE IMPROVEMENT BY BURR GRINDING	*DATA SHEET*

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W

Filler material: CSA W48.5M, Class E4801T-9CH

Welding procedure no.: S155

Identification: 4FBG9

Operator Experience: Less than 10 hrs

Training program: Less than 1 meter

EQUIPMENT

Type: Pneumatic - UG 25NSA

Power: Air driven

Diameter tip: 12 mm (type F/SF-5)

Weight (with tip): 0.72 kg

Rotation speed: 25,000 rpm

DATA

Position: Overhead (4F)

Work angle: 45°

Deplacement angle: Backhand 30° - 45°

Travel speed: 175 mm/mn (10.50 metre/hour)

Nbr of passes: 3 (first side) and 2 (second side)

Length of treatment: 1250 mm

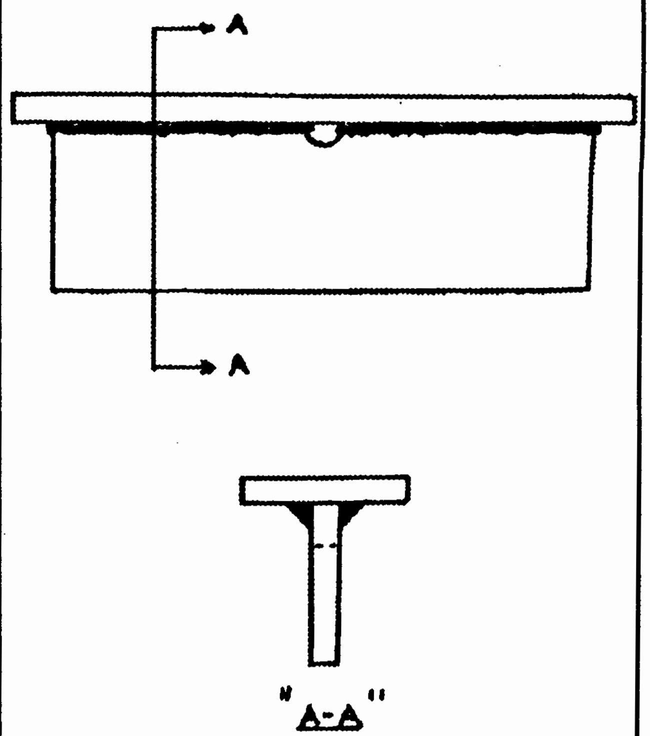
Time of treatment: 429 sec.

Change of tool: New tip (type F/SF-5)

Time: –

Cause: –

SCHEMATIC DIAGRAM



INSPECTION

■ Visual ■ Dimensional

Equipment: Rule and weld gauge

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	2.00	2.00	2.50
Groove depth (mm):	0.50	0.25	1.00

Macrographic report: M99

REMARKS

1. Upward and downward motion.
2. Removal of metal more accentuated on wraps.

Operator: Christian Fortier (6062)

Date: August 28, 1996

File C:\1996\INGPROD CF\TABLEAU\WTIBG\BG0001

COMPANY NAME (Address)	WELD TOE IMPROVEMENT BY BURR GRINDING	*DATA SHEET*

WELDING SPECIFICATION

Base material: ______________________

Filler material: ______________________

Welding procedure no.: ______________________

Identification: ______________________

Operator Experience: ______________________

Training program: ______________________

EQUIPMENT

Type: ______________________

Power: ______________________

Diameter tip: ______________________

Weight (with tip): ______________________

Rotation speed: ______________________

DATA

Position: ______________________

Work angle: ______________________

Deplacement angle: ______________________

Travel speed: ______________________

Nbr of passes: ______________________

Length of treatment: ______________________

Time of treatment: ______________________

Change of tool: ______________________

Time: ______________________

Cause: ______________________

SCHEMATIC DIAGRAM

Identification: ______________________

INSPECTION

☐ Visual ☐ Dimensional

Equipment: ______________________

RESULTS

	Mean	Min.	Max.
Toe radius (mm):			
Groove depth (mm):			
Macrographic report:			

REMARKS

Operator: ______________________ Date: ______________________

APPENDIX B

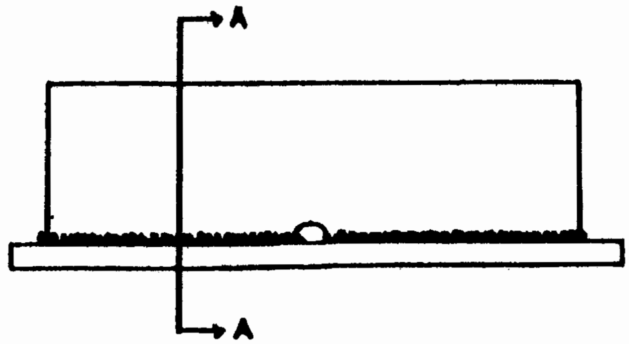
PRODUCTION DATA SHEETS FOR WELD FATIGUE IMPROVEMENT BY TIG DRESSING

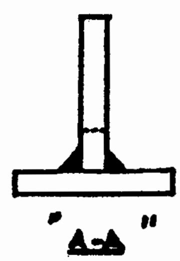
THE MIL GROUP INC. 22 George D. Davie (P.O. Box 130) Lévis (Québec) G6V 6N7 Phone (418) 837-5941	WELD TOE IMPROVEMENT BY TIG DRESSING	*DATA SHEET*

WELDING SPECIFICATION	
Base material: CA G40.21M, Gr. 300W	Identification: 2FTD4
Filler material: CSA W48.5M, Class E4801T-9CH	Operator Experience: Less than 10 hrs
Welding procedure no.: S155	Training program: Less than 1 meter

EQUIPMENT	
Type:	Syncrowave 250 AC/DC - Miller
Electrode diameter:	3.2 mm - Class EWTh-2
Gas cup diameter:	12 mm
High frequency:	Start only - Intensity 10
Shielding gas:	Argon (99.9%)

SCHEMATIC DIAGRAM





DATA	
Position:	Horizontal (2F)
Work angle:	60°
Deplacement angle:	Forehand 10°
Welding parameters:	210A - 13V
Travel speed:	127 mm/mn (7.62 metre/hour)
Heat input	1.3 Kj/mm
Nbr of passes:	1 (both sides of weld bead)
Length of treatment	1200 mm
Time of treatment	565 sec.
Change of electrode:	Regrinding one time
Time:	–
Cause:	Touch with piece

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	2.50	2.00	3.00
Groove depth (mm):	0.10	0.00	0.40
Macrographic report	M94		

REMARKS

1. Arc weaving (light oscillation) ≈ 2 mm.

Operator: Christian Fortier (6062)	Date: August 28, 1996

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The MIL Group Inc.
WELDING AND METALLURGY
R&D CENTRE

MACROGRAPHIC EVALUATION

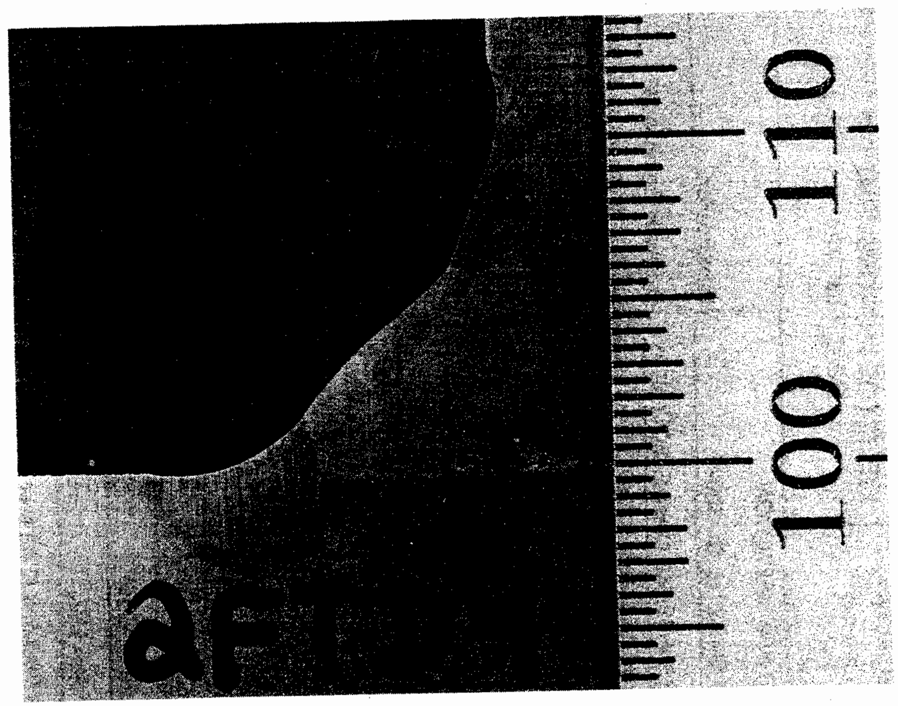
REPORT No.: M-94

STANDARD: ASTM E-340
BASE METAL: 300W
FILLER MATERIAL: LA-T-91

WELDING ASSEMBLY #: S155
ETCHANT/TIME OF ETCHING: Nital 10%/10 sec.
TEST TEMPERATURE: 20°C

DATE: August 28, 1996
MOTHER PLATE ID: —
ASSEMBLY PLATES ID: 2FTD4

SPECIMEN ID	NUMBER OF DEFECTS			TYPE, SIZE AND ORIENTATION OF DEFECTS
	BASE METAL	FILLER METAL	FUSION LINE	
2FTD4				



REMARKS: HORIZONTAL POSITION

Christian Fortier (6062) SIGNATURE
August 28, 1996 DATE

SIGNATURE
DATE

File B:\ME0094

THE MIL GROUP INC.
22 George D. Davie (P.O. Box 130)
Lévis (Québec) G6V 6N7
Phone (418) 837-5941

WELD TOE IMPROVEMENT BY TIG DRESSING

DATA SHEET

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W
Filler material: CSA W48.5M, Class E4801T-9CH
Welding procedure no.: S155

Identification: 3FTD5
Operator Experience: Less than 10 hrs
Training program: Less than 1 meter

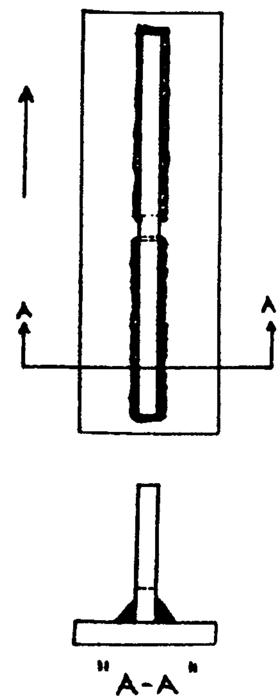
EQUIPMENT

Type: Syncrowave 250 AC/DC - Miller
Electrode diameter: 3.2 mm - Class EWTh-2
Gas cup diameter: 12 mm
High frequency: Start only - Intensity 10
Shielding gas: Argon (99.9%)

DATA

Position: Vertical upward
Work angle: 70°
Deplacement angle: Forehand 10°
Welding parameters: 170A - 12V
Travel speed: 122 mm/mn (7.32 metre/hour)
Heat input: 1.0 Kj/mm
Nbr of passes: 1 (both sides of weld bead)
Length of treatment: 1200 mm
Time of treatment: 588 sec.
Change of electrode: –
Time: –
Cause: –

SCHEMATIC DIAGRAM



RESULTS

	Mean	Min.	Max.
Toe radius (mm):	3.00	2.50	3.50
Groove depth (mm):	0.10	0.00	0.20

Macrographic report: M95

REMARKS

1. Arc weaving (light oscillation) ≈ 2 mm.

Operator: Christian Fortier (6062)
Date: August 28, 1996

File C:\1996\INGPROD CF\TABLEAU\WTITD\TD0002

THE MIL GROUP INC. 22 George D. Davie (P.O. Box 130) Lévis (Québec) G6V 6N7 Phone (418) 837-5941	WELD TOE IMPROVEMENT BY TIG DRESSING	*DATA SHEET*

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W

Filler material: CSA W48.5M, Class E4801T-9CH

Welding procedure no.: S155

Identification: 4FTD6

Operator Experience: Less than 10 hrs

Training program: Less than 1 meter

EQUIPMENT

Type: Syncrowave 250 AC/DC - Miller

Electrode diameter: 3.2 mm - Class EWTh-2

Gas cup diameter: 12 mm

High frequency: Start only - Intensity 10

Shielding gas: Argon (99.9%)

DATA

Position: Overhead

Work angle: 60°

Deplacement angle: Forehand 10°

Welding parameters: 170A - 12V

Travel speed: 134 mm/mn (8.04 metre/hour)

Heat input 0.9 Kj/mm

Nbr of passes: 1 (both sides of weld bead)

Length of treatment 1200 mm

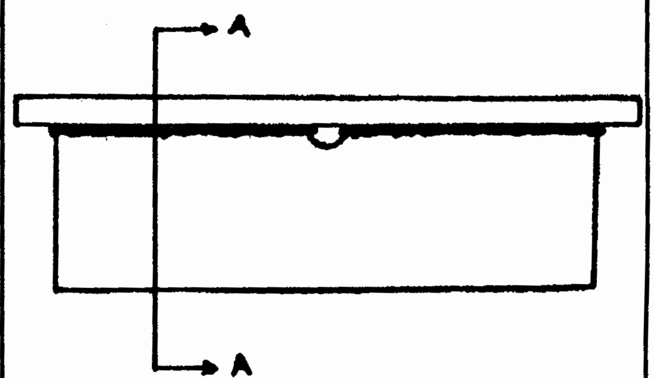
Time of treatment 539 sec.

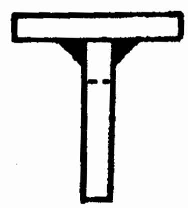
Change of electrode: –

Time: –

Cause: –

SCHEMATIC DIAGRAM





"A-A"

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	3.50	3.00	4.00
Groove depth (mm):	0.20	0.00	0.50
Macrographic report	M96		

REMARKS

1. Arc weaving (light oscillation) ≈ 2 mm.

Operator: Christian Fortier (6062)

Date: August 28, 1996

File C:\1996\INGPROD CF\TABLEAU\WTITD\TD0001

COMPANY NAME (Address)	WELD TOE IMPROVEMENT BY TIG DRESSING	*DATA SHEET*

WELDING SPECIFICATION

Base material: ____________________

Filler material: ____________________

Welding procedure no.: ____________________

Identification: ____________________

Operator Experience: ____________________

Training program: ____________________

EQUIPMENT

Type: ____________________

Electrode diameter: ____________________

Gas cup diameter: ____________________

High frequency: ____________________

Shielding gas: ____________________

DATA

Position: ____________________

Work angle: ____________________

Deplacement angle: ____________________

Welding parameters: ____________________

Travel speed: ____________________

Heat input: ____________________

Nbr of passes: ____________________

Length of treatment: ____________________

Time of treatment: ____________________

Change of electrode: ____________________

Time: ____________________

Cause: ____________________

SCHEMATIC DIAGRAM

Identification: ____________________

____

____

____

RESULTS

	Mean	Min.	Max.
Toe radius (mm):			
Groove depth (mm):			
Macrographic report:			

REMARKS

____

____

____

____

____

Operator: ____________________

Date: ____________________

AUTOMATIC MACRO HARDNESS REPORT

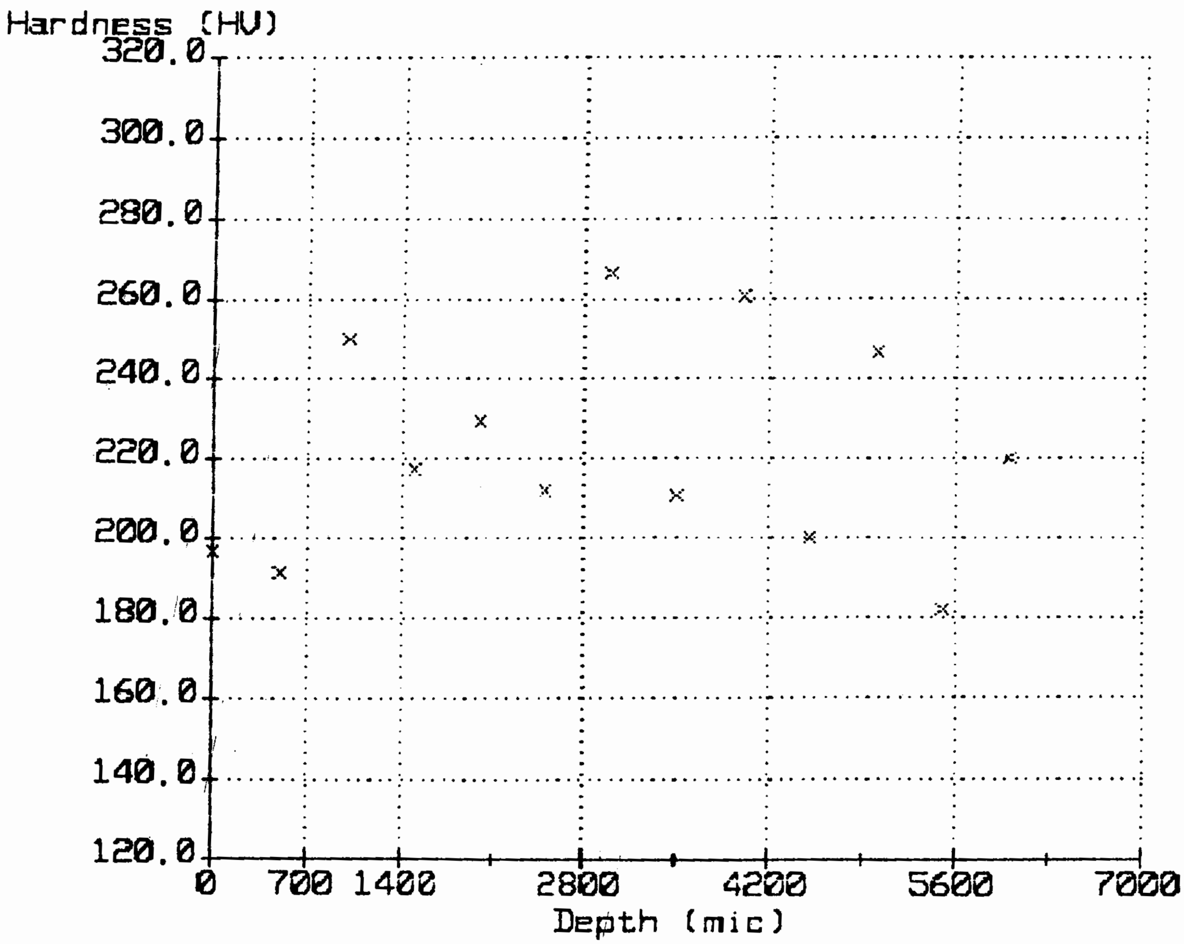
Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-28-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-1
Misc : Centre R & D soudage

Hardness vs depth



File name : No Name

Average : 222 HV
Std. dev. : 27.1 HV
Minimum : 182 HV
Maximum : 267 HV

AUTOMATIC MACRO HARDNESS REPORT

Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-28-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-1
Misc : Centre R & D soudage

No.	Depth (mic)	Hardness
1	0	197 HV
2	500	192 HV
3	1000	250 HV
4	1500	218 HV
5	2000	230 HV
6	2500	212 HV
7	3000	267 HV
8	3500	211 HV
9	4000	261 HV
10	4500	201 HV
11	5000	247 HV
12	5500	182 HV
13	6000	221 HV

AUTOMATIC MACRO HARDNESS REPORT

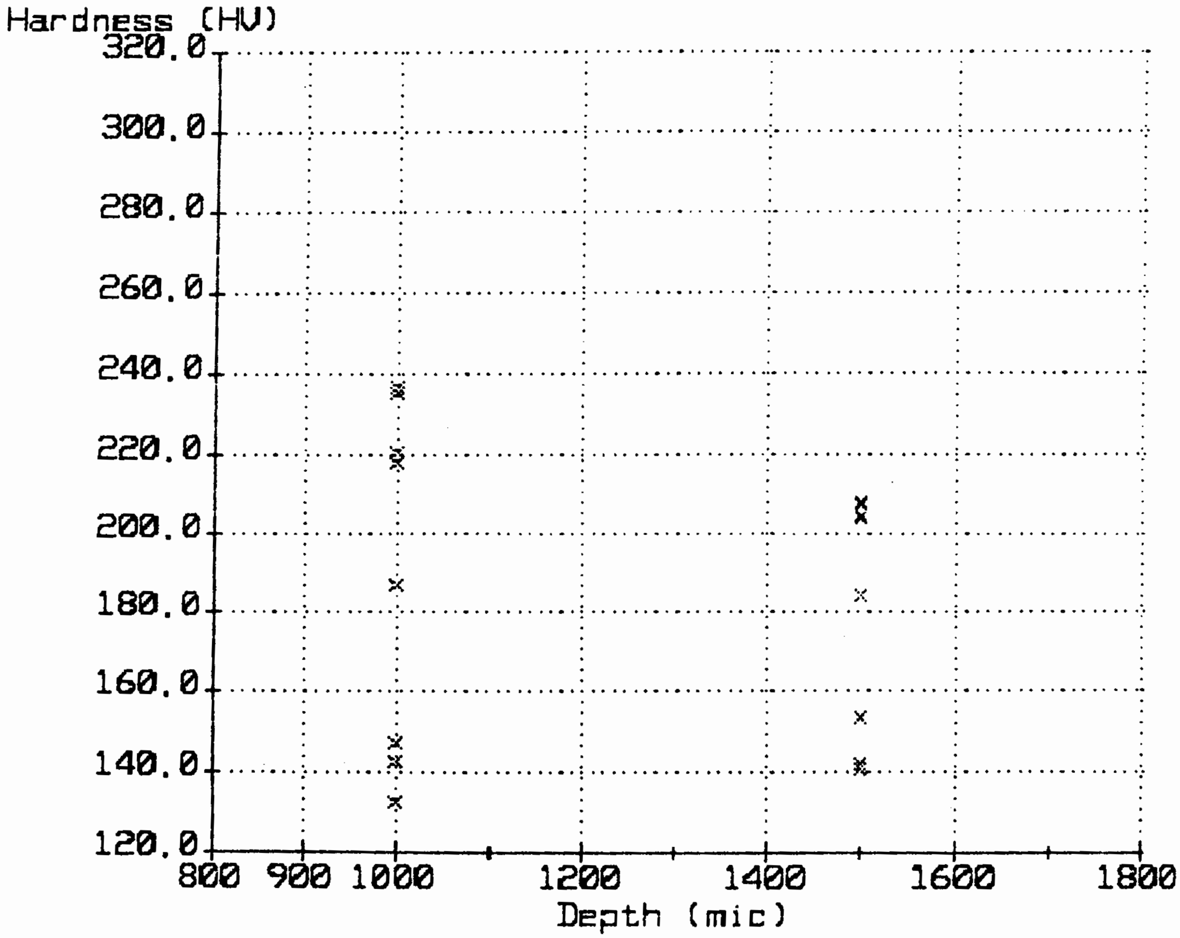
Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-28-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-2
Misc : Centre R & D soudage

Hardness vs depth



File name : No Name

Average : 190 HV
Std. dev : 36.7 HV
Minimum : 133 HV
Maximum : 237 HV

AUTOMATIC MACRO HARDNESS REPORT

Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-28-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-2
Misc : Centre R & D soudage

No.	Depth (mic)	Hardness	
1	1000	133 HV	
2	1500	141 HV	
3	1000	143 HV	
4	1500	143 HV	
5	1000	148 HV	
6	1500	153 HV	
7	1000	187 HV	
8	1500	185 HV	
9	1000	218 HV	
10	1500	208 HV	
11	1000	236 HV	226
12	1000	236 HV	
13	1500	208 HV	
14	1000	237 HV	
15	1500	208 HV	
16	1000	221 HV	
17	1500	205 HV	[illegible]
18	1500	204 HV	

AUTOMATIC MACRO HARDNESS REPORT

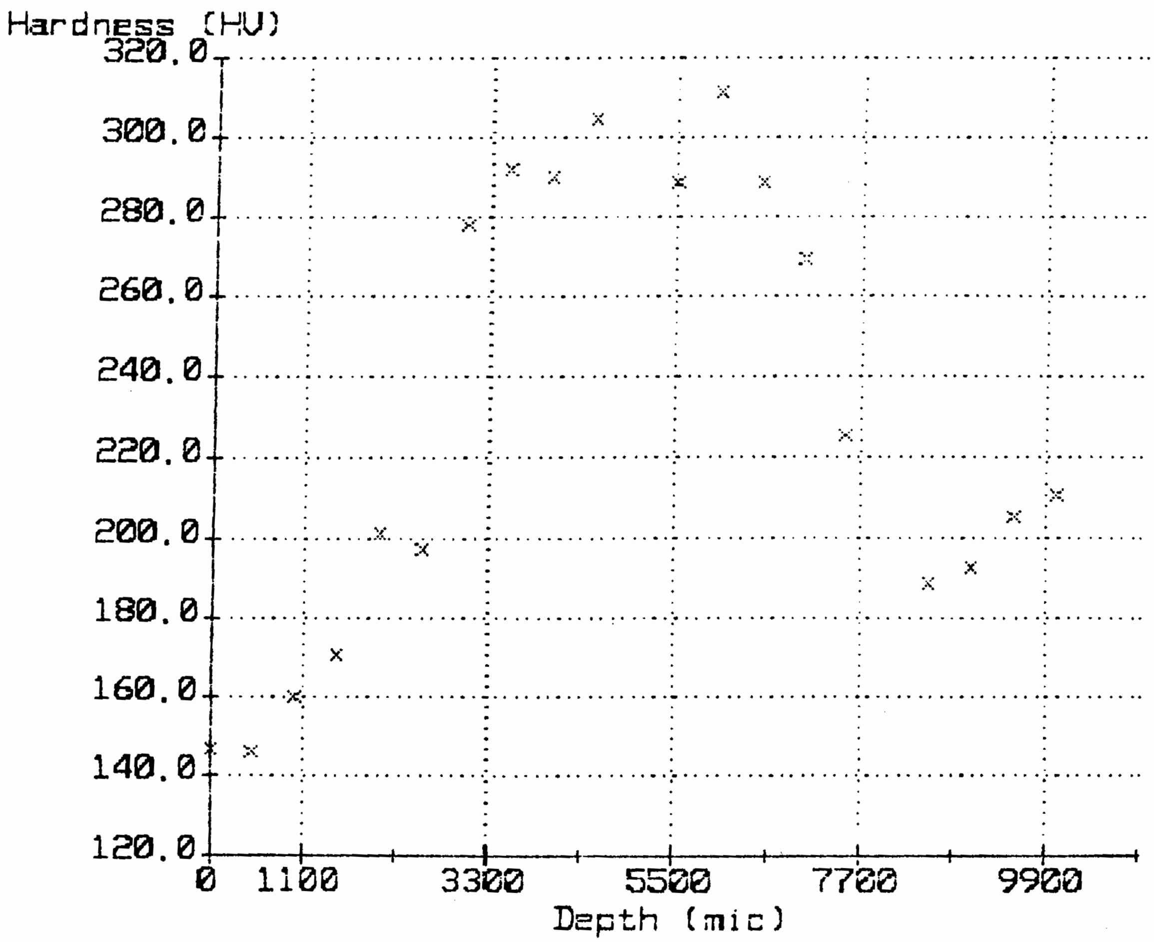
Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-30-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-3
Misc : Centre R & D soudage

Hardness vs depth



File name : No Name

Average : 235 HV
Std. dev. : 59.6 HV
Minimum : 146 HV
Maximum : 325 HV

AUTOMATIC MACRO HARDNESS REPORT

Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-30-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-3
Misc : Centre R & D soudage

No.	Depth (mic)	Hardness
1	0	147 HV
2	500	146 HV
3	1000	160 HV
4	1500	171 HV
5	2000	201 HV
6	2500	198 HV
7	3000	278 HV
8	3500	292 HV
9	4000	290 HV
10	4500	305 HV
11	5000	325 HV
12	5500	289 HV
13	6000	312 HV
14	6500	289 HV
15	7000	270 HV
16	7500	226 HV
17	8500	189 HV
18	9000	193 HV
19	9500	205 HV
20	10000	211 HV

AUTOMATIC MACRO HARDNESS REPORT

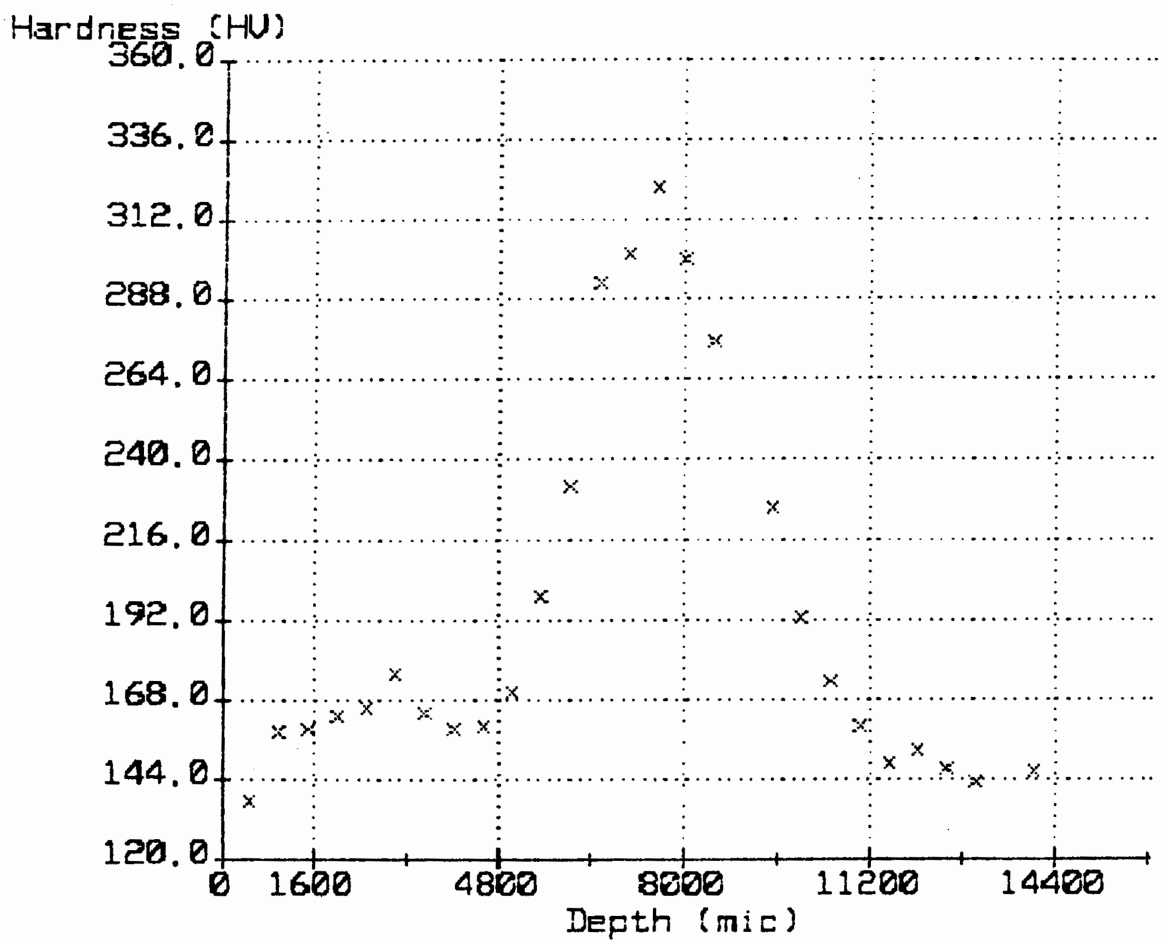
Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-30-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-4
Misc : Centre R & D soudage

Hardness vs depth



File name : No Name

Average : 194 HV
Std. dev. : 57.2 HV
Minimum : 138 HV
Maximum : 322 HV

AUTOMATIC MACRO HARDNESS REPORT

Company name : WELD TOE TREATMENT/MSEI
User name : CHRISTIAN FORTIER
Cal. : 1.477e+00 mic /pix
Load : 10.000 kg

Date : 8-30-96
Lens : 10x
Diamond : Vickers

The last diamond calibration was done at 11:14:45 on 7-29-96, with a test block of 301 HV and a load of 10000g.

Sample id : DU97-4
Misc : Centre R & D soudage

No.	Depth (mic)	Hardness
1	500	138 HV
2	1000	159 HV
3	1500	160 HV
4	2000	164 HV
5	2500	166 HV
6	3000	177 HV
7	3500	165 HV
8	4000	159 HV
9	4500	160 HV
10	5000	171 HV
11	5500	200 HV
12	6000	233 HV
13	6500	293 HV
14	7000	302 HV
15	7500	322 HV
16	8000	300 HV
17	8500	275 HV
18	9500	226 HV
19	10000	193 HV
20	10500	174 HV
21	11000	160 HV
22	11500	149 HV
23	12000	153 HV
24	12500	148 HV
25	13000	144 HV
26	14000	146 HV

APPENDIX C

PRODUCTION DATA SHEETS FOR WELD FATIGUE IMPROVEMENT BY HAMMER PEENING

THE MIL GROUP INC.
22 George D. Davie (P.O. Box 130)
Lévis (Québec) G6V 6N7
Phone (418) 837-5941

WELD TOE IMPROVEMENT BY HAMMER PEENING

DATA SHEET

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W

Filler material: CSA W48.5M, Class E4801T-9CH

Welding procedure no.: S155

Identification: 2FHP1

Operator Experience: Less than 10 hrs

Training program: Less than 1 meter

EQUIPMENT

Type: Pneumatic

Power: Air driven

Diameter tip: 9 to 12 mm

Weight (with tip): 1.8 kg

Blows per second: 92

DATA

Position: Horizontal (2F)

Work angle: 45°

Deplacement angle: Forehand 10°

Travel speed: 69 mm/mn (4.14 metre/hour)

Nbr of passes: 4 (both sides of weld bead)

Length of treatment: 1230 mm

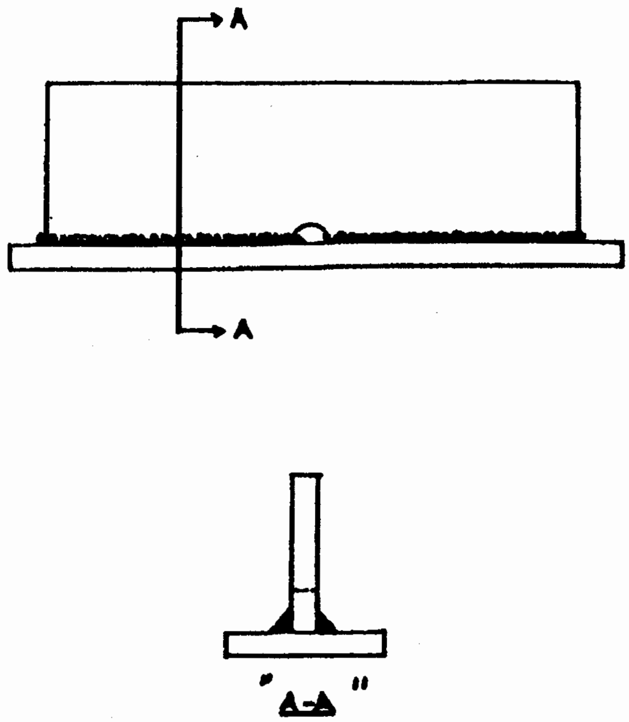
Time of treatment: 1074 sec.

Change of tool: –

Time: –

Cause: –

SCHEMATIC DIAGRAM



INSPECTION

■ Visual ■ Dimensional

Equipment: Rule and weld gauge

REMARKS

1. Backward and forward motion.

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	4.50	4.00	5.00
Groove depth (mm):	0.25	0.00	0.50

Macrographic report: M91

Operator: Christian Fortier (6062)

Date: August 28, 1996

File C:\1996\INGPROD CF\TABLEAU\WTIBG\HP0001

The MIL Group Inc.
WELDING AND METALLURGY
R&D CENTRE

MACROGRAPHIC EVALUATION

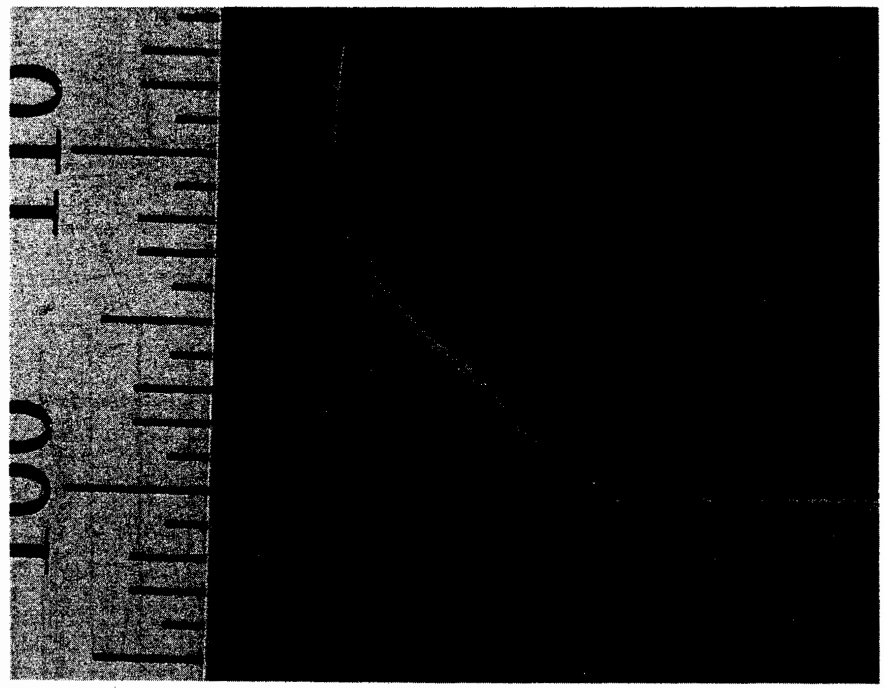
REPORT No.: M-91

STANDARD: ASTM E-340
BASE METAL: 300W
FILLER MATERIAL: LA-T-91

WELDING ASSEMBLY #: S155
ETCHANT/TIME OF ETCHING: Nital 10%/10 sec.
TEST TEMPERATURE: 20°C

DATE: August 28, 1996
MOTHER PLATE ID: —
ASSEMBLY PLATES ID: 2FHP1

SPECIMEN ID	NUMBER OF DEFECTS			TYPE, SIZE AND ORIENTATION OF DEFECTS
	BASE METAL	FILLER METAL	FUSION LINE	
2FHP1				



REMARKS: HORIZONTAL POSITION

Christian Fortier (6062)
SIGNATURE

August 28, 1996
DATE

SIGNATURE

DATE

File B:\ME0091

THE MIL GROUP INC. 22 George D. Davie (P.O. Box 130) Lévis (Québec) G6V 6N7 Phone (418) 837-5941	WELD TOE IMPROVEMENT BY HAMMER PEENING	***DATA SHEET***

WELDING SPECIFICATION	
Base material: CA G40.21M, Gr. 300W	Identification: 3FHP2
Filler material: CSA W48.5M, Class E4801T-9CH	Operator Experience: Less than 10 hrs
Welding procedure no.: S155	Training program: Less than 1 meter

EQUIPMENT

Type: Pneumatic

Power: Air driven

Diameter tip: 9 to 12 mm

Weight (with tip): 1.8 kg

Blows per second: 92

DATA

Position: Vertical upward (3F)

Work angle: 45°

Deplacement angle: Forehand 10°

Travel speed: 87 mm/mn (5.22 metre/hour)

Nbr of passes: 5 (first side) and 4 (second side)

Length of treatment: 1240 mm

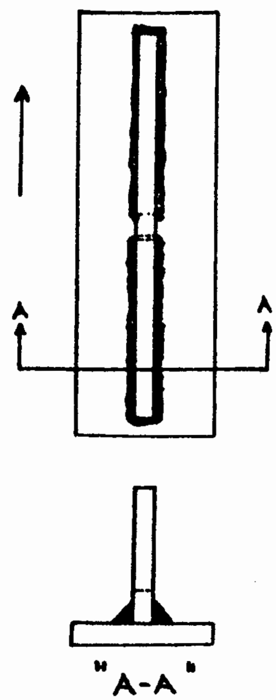
Time of treatment: 853 sec.

Change of tool: Regrinding after first side of weld bead

Time: –

Cause: Deformation

SCHEMATIC DIAGRAM



INSPECTION

■ Visual ■ Dimensional

Equipment: Rule and weld gauge

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	4.50	4.00	5.00
Groove depth (mm):	0.10	0.00	0.20

Macrographic report: M92

REMARKS

1. Upward and forward motion.

Operator: Christian Fortier (6062)

Date: August 28, 1996

File C:\1996\INGPROD CF\TABLEAU\WTIBG\HP0002

THE MIL GROUP INC. 22 George D. Davie (P.O. Box 130) Lévis (Québec) G6V 6N7 Phone (418) 837-5941	WELD TOE IMPROVEMENT BY HAMMER PEENING	DATA SHEET

WELDING SPECIFICATION

Base material: CA G40.21M, Gr. 300W

Filler material: CSA W48.5M, Class E4801T-9CH

Welding procedure no.: S155

Identification: 4FHP3

Operator Experience: Less than 10 hrs

Training program: Less than 1 meter

EQUIPMENT

Type: Pneumatic

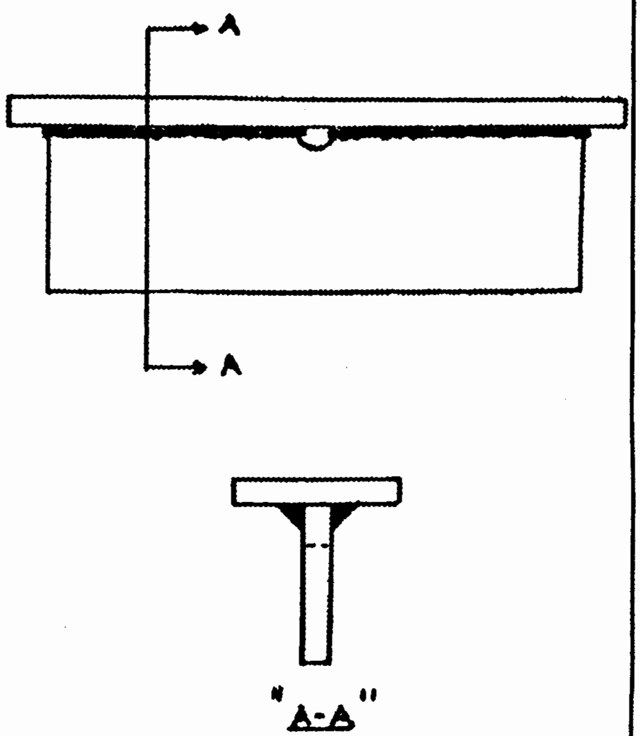
Power: Air driven

Diameter tip: 9 to 12 mm

Weight (with tip): 1.8 kg

Blows per second: 92

SCHEMATIC DIAGRAM



DATA

Position: Overhead (4F)

Work angle: 45°

Deplacement angle: Forehand 10°

Travel speed: 91 mm/mn (5.46 metre/hour)

Nbr of passes: 5 (both sides of weld bead)

Length of treatment: 1240 mm

Time of treatment: 822 sec.

Change of tool: –

Time: –

Cause: –

INSPECTION

■ Visual ■ Dimensional

Equipment: Rule and weld gauge

REMARKS

1. Backward and forward motion.

RESULTS

	Mean	Min.	Max.
Toe radius (mm):	4.50	4.00	5.00
Groove depth (mm):	0.00	0.00	0.00
Macrographic report:	M93		

Operator: Christian Fortier (6062)

Date: August 28, 1996

File C:\1996\INGPROD CF\TABLEAU\WTIBG\HP0001

COMPANY NAME (Address)	WELD TOE IMPROVEMENT BY HAMMER PEENING	***DATA SHEET***

WELDING SPECIFICATION	
Base material: ______	Identification: ______
Filler material: ______	Operator Experience: ______
Welding procedure no.: ______	Training program: ______

EQUIPMENT	*SCHEMATIC DIAGRAM*
Type: ______	
Power: ______	
Diameter tip: ______	
Weight (with tip): ______	
Blows per second: ______	
DATA	
Position: ______	
Work angle: ______	
Deplacement angle: ______	
Travel speed: ______	
Nbr of passes: ______	
Length of treatment: ______	Identification: ______
Time of treatment: ______	______
Change of tool: ______	______
Time: ______	______
Cause: ______	

INSPECTION	*REMARKS*
☐ Visual ☐ Dimensional	______
Equipment: ______	______
______	______
______	______
RESULTS	______
Mean Min. Max.	______
Toe radius (mm): ______	______
Groove depth (mm): ______	
Macrographic report: ______	

Operator: Christian Fortier (6062)	Date: August 28, 1996

PROJECT TECHNICAL COMMITTEE MEMBERS

The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, performed technical review of the work in progress and edited the final report.

Chairman	Mr. W. Thomas Packard, NAVSEA
Members	Mr. Mike Sieve, NAVSEA
	Mr. Jim Sawhill, Newport News Shipbuilding
	Mr. H. Paul Cojeen, USCG
	Mr. Jaideep Sirkar, USCG
	Mr. Jim White, USCG R&D Center
	Mr. Bill Tyson, CANMET
	Mr. Bill Hanzelek, ABS
	LT John Cushing, USCG MSC
Contracting Officer's Technical Representative:	Mr. William Siekierka, NAVSEA
Marine Board Liaison:	Dr. Robert Sielski, National Academy of Science
Executive Director Ship Structure Committee:	LT Thomas C. Miller, USCG CDR Steve Sharpe, USCG