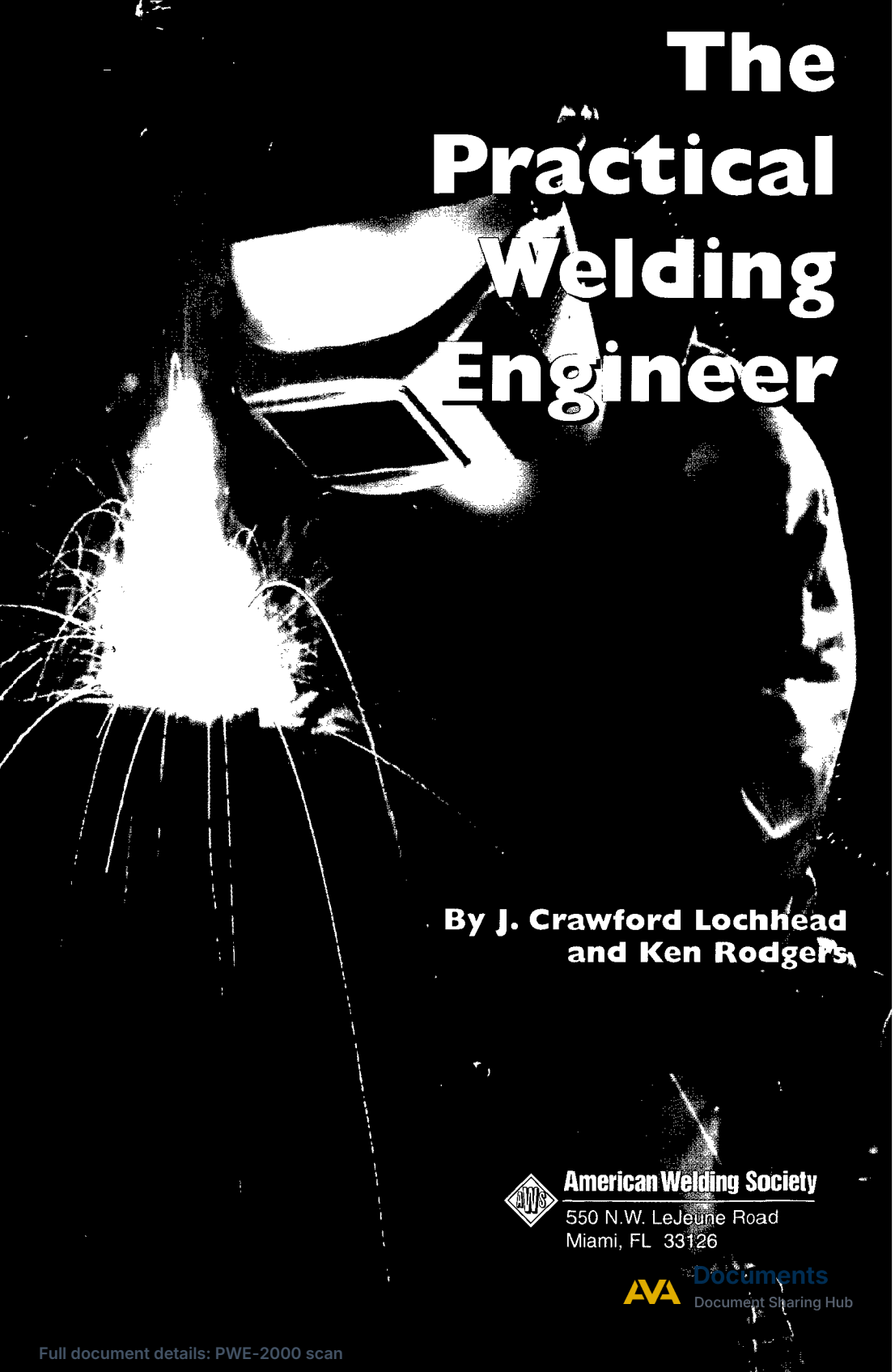




The Practical Welding Engineer

**By J. Crawford Lochhead
and Ken Rodgers**



American Welding Society

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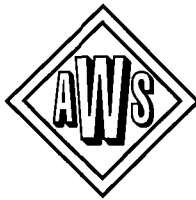
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**By
J. Crawford Lochhead
and
Ken Rodgers**

**Brown and Root McDermott
Fabricators, Ltd.,
Inverness, Scotland.**



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International Standard Book Number: 0-87171-620-8
American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126
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Text edited by Tim Heston.

Printed in the United States of America

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Preface

When we, the authors, decided to write this book, we had a definite aim in mind — to present a “practical” approach to the application of welding theories.

Over recent years universities and colleges have recognized the previous lack of attention paid to the welding fraternity and subsequently greatly improved teaching capabilities and lecture contents. As a result, the modern engineer is well versed in basic metallurgical behavior; he is aware of the application of electronic wizardry to modern equipment; fracture mechanics is not just an obscure theory but a practical everyday tool; and, modern materials and consumables have apparently eliminated many of the problems of the past. What the modern welding engineer lacks is the knowledge of how to apply this knowledge in a practical sense. What we have attempted to write is basically a distillation of almost 60 years (between the two of us) of hard-gained realism in heavy engineering fabrication.

The basis of the book is therefore an assumption that the reader is already knowledgeable of basic welding and metallurgical theory. He is most likely a metallurgist, materials science or mechanical engineering graduate who, during his or her university career has stumbled, or been fortuitously directed, into the welding field. It is obviously a biased view, but in the opinion of the authors, welding is one of the most exciting fields available to a young graduate. It is both vibrant and dynamic with new avenues to be explored becoming available on a regular basis. Synergic gas metal arc welding and inverter power sources, electron and laser welding, magnetic-impelled arc butt-joint welding (MIAB), robotic welding, and diffusion bonding are careers in themselves. It is difficult to identify another discipline where the range of possibilities are as diverse, broad, and exciting, and where the potentials for exploration and discovery stretch enticingly into the future.

However, enough of such esoteric digressions. This book was not written from that approach. It is intended to present the inexperienced welding engineer with some “sage” advice on some of the pitfalls awaiting in the hard commercial world that awaits. Be under no illusions; it is not sufficient to be the best theoretical welding engineer in your company. You must know how to apply that knowledge in an almost “street-wise” manner.

Welding is regarded by many employers as a “black art.” Some of this reputation has been due to welding engineers camouflaging their inadequacies, or uncertainties, with professional jargon. Telling one’s employer that the problem is one of “cracking initiated in a highly tensile stressed region of hard martensite or body centered cubic microstructure of poor crack resistance surrounded by material of similar sensitivity to crack propagation into which atomic hydrogen has diffused, and that until the diffusion rate is beneficially altered the problem will persist,” is not clear. Telling him that you have identified the problem to be “one of delayed hydrogen cracking and that increasing the preheat temperature by 25°C will resolve it” will undoubtedly raise your standing in the company — unless you have an enlightened employer who asks you why you didn’t recognize that a higher preheat was necessary in the first place.

The book is entitled “The Practical Welding Engineer.” We hope you find it to be practical. We also hope that, although you may not totally or even partially agree with its contents, you find it readable and interesting.

Good Reading

J. C. Lochhead and K. J. Rodgers

Acknowledgments

The authors would like to thank the following personnel for their assistance in the execution of this work.

T. Clement and M. Dorricott, Managing Directors, Brown & Root Highlands Fabricators Ltd.

D. J. Wright, Managing Director, Brown and Root McDermott Fabricators, Ltd.

I. G. Hamilton, Consultant (for general advice).

Dr. W. Welland, for assistance with run-out/stub length information.

Mrs. Patricia Vass and Claire Lochhead, for general secretarial assistance.

All other suppliers of photographs, tables, suggestions, etc.

The authors would also like to thank Training Publications, Ltd., Watford, England, for permission to use data and Figures 8.1–8.9 and 8.11–8.13 extracted from Module Manual F10 of the *General Welding and Cutting for Engineering Craftsmen* manual. Permission is not transferable.

Chapter 1

Contracts and the Role of the Welding Engineer

This may appear to be a strange starting point for a book intended to assist a welding engineer. However, it must be appreciated at an early stage that, as is common with most disciplines, decisions based on technical judgments must be tempered with economic awareness. In general, there can be several possible solutions (and hence several possible costs) for any one problem. The principle behind every commercial venture is to make a profit, and the welding engineer must always remember that what leaves the factory gates is what pays his wages. It may leave in a timely manner, and it may be of the finest quality; but it also must be profitable.

Commercial awareness usually is presented as an unessential part of the welding engineer's discipline. This thinking is misguided because in most fabrications welding plays a primary role of cost containment. If it is not right, either technically or commercially, the company's profitability will suffer. This is an aspect that still is not sufficiently recognized by many companies and engineers.

This chapter will deal with two aspects in some detail — commercial awareness, and dealing with specifications.

1.1 Commercial Awareness

This section is not intended to be a detailed study of the commercial management of a project. It is intended simply to make you, the welding engineer, aware and appreciative of the key links and actions in the chain of events that will ensure your company is fully compensated for everything it does for a client — or, conversely, receives everything it is paying for as a client.

The following subjects will be discussed:

1. What is commercial awareness?
2. Making a profit.
3. The key elements of a contract.
4. Ensuring the company is fully compensated (or receives a full service).
5. Variations and claims.

In all of these elements there are fundamental points applicable to the welding engineer, regardless of the size of the company in which he operates. They may not be instantly recognizable under the descriptions given. However, they will exist in some form, and the welding engineer should play a leading role in all these aspects.

1.1.1 What is Commercial Awareness?

In simple terms, commercial awareness is the need for everyone to carry out their work in such a way that the company makes a profit.

This means that

- estimates for welding should be constructed on the basis of sound judgments and well-defined logic,
- everything should be done right the first time and completed in the most cost-effective and economic manner, and
- everything possible should be done to maximize revenue and reduce expenditure.

These objectives can be achieved only if the welding engineer is fully aware of his role and of the cost and planning parameters that control his functions.

1.1.2 Making a Profit

Profit is the lifeblood of any company. The essential ingredients that will ensure a company makes a profit are

- a good cost and price estimate,
- a good plan,
- an ability to manage both people and work efficiently,
- quality (get it right the first time),
- safety (bad practices cost money),
- cost-effective execution of all work, and
- maximizing revenue (i.e., ensuring that the company is paid in full for everything it does).

1.1.3 Key Elements of a Contract

The seven key elements of a contract are

1. the tender (i.e., the bid),
2. the plan,
3. the scope of work,
4. purchasing,
5. subcontracting,
6. measurement and evaluation of the work, and
7. contractual obligations.

On first impression, the welding engineer may perceive that few of these aspects are applicable to him. This is erroneous. In fact, the welding engineer should have a fundamental role in every phase of the contract from the preparation of a tender to the fulfillment of the last contractual obligation; and greater emphasis on this role should be undertaken by the conscientious engineer. The seven key elements presented above will now be described briefly.

The Tender

The key elements of a tender (i.e., the bid) that form the criteria against which the job will be measured are

- specifications,
- drawings,
- scope of work,
- procedures,
- resources,
- methods, and
- price.

The tender describes the criteria and assumptions upon which the work is priced and planned, and it establishes the base from which all changes will be measured. Therefore, it is of paramount importance to define clearly the data and assumptions used in compiling the price and plan. In addition, it must be made clear that if the assumptions are wrong, or if they are not acceptable to the client, then there will be an effect on the price, or the delivery date, or both. All factors and calculations used in compiling the price and plan must be clearly recorded and retained throughout the life of the contract. Remember, they will form the basis for any cost adjustments resulting from changes.

The Plan

The plan describes how, when, and where the work will be carried out, as well as the resources to be used. There are many instances when the time allowed by a client for the tender period is very short, and the information relating to the scope of work and deliverables is incomplete. This combination of factors complicates the development of a comprehensive plan. Nevertheless, the aim should be to develop an accurate plan that represents the way the work is intended to be carried out. The plan is the base from which the *effect* of all changes will be measured, and this includes self-induced changes.

The Scope of Work

In an ideal situation, the work would be executed strictly in accordance with the original plan and cost estimate. In the real world, however, this rarely happens — usu-

ally because the work is insufficiently defined at the time of the tender. It is important that the people who are responsible for executing the work are fully aware of how the work was planned and costed, so they can operate within their parameters or can identify and notify change to the same. The identification and notification of changes is the most important link in the chain of events that leads to payment for the effects of changes.

Purchasing

Cost-effective purchasing is a key factor in successfully executing a contract. At the tender stage, delivery dates and prices for all required materials should be obtained. After the contract is awarded, it is important that materials are procured in accordance with the needs of the production department — that is, in accordance with the plan and within the quoted prices. Additionally, if items such as new welding machines or consumables are necessary for the job, sufficient notice should be given by the welding engineer to the relevant departments to obtain adequate quotations. Any relevant purchase lead-times also must be included in the plan.

Subcontracting

Regardless of the size of the subcontract, the rules are the same. The subcontract must

- clearly define the scope of work,
- specify the dates for deliverables to the subcontractor,
- agree to a schedule for completion, and
- specify the services to be provided (if any) to the subcontractor.

Subsequent changes in specifications given to the subcontractor should be minimized. If this is unavoidable, any effects must be properly monitored. It is the responsibility of the welding engineer to ensure that all necessary approvals of the subcontractors' welding procedures, etc., are made on time; otherwise, claims for consequential delays are likely to appear on his desk.

Measurement and Evaluation of the Work

There are a number of ways of measuring the work, but the two most common are

- lump-sum pricing with a schedule of rates, in which only variations are measured; and
- lump-sum pricing based on a bill of quantities, and a schedule of rates, in which all of the work is measured.

The work is measured from the drawings, and all changes that flow through drawings should be picked up in that measurement. Of course, the increased work resulting from a change to drawings would be picked up in a subsequent re-measure and valued at the schedule rates, and the effect of the increase on the schedule would warrant a claim for extending the duration of the contract.

Changes initiated by means other than drawings are the subject of variation orders, for example,

- changes in specification,
- changes in timing, and
- changes in design after work has been completed.

Generally, such changes would be measured as an effect on the cost of labor, equipment, and facilities and would be priced accordingly — not on the basis of the schedule of unit rates.

Contractual Obligations

The major contractual obligations that affect the performance of the work are:

- execution of the work in accordance with drawings and specifications;
- execution of the work in accordance with the schedule, unless it can be proven that this has been prevented by factors beyond the company's control;
- provision that work is free from defects (noting that, even where work has been inspected and/or certified, the manufacturer is liable for any defects that may be found subsequently; and, while a contractual obligation extends through to the end of the maintenance period, a common-law and/or moral obligation extends far beyond that date);
- appreciation that approval of drawings, method statements, weld procedures, etc., do not relieve the company from contractual obligations;
- appreciation that inspectors and certifications by certifying authorities do not relieve the company from contractual obligations; and
- knowledge that, in cases where the client causes disruption or delay to the progress of the work, the contractor has an obligation to minimize the effect of the same, provided such mitigation does not add to its cost.

1.1.4 Ensuring the Company Is Fully Compensated

The welding engineer can make a significant contribution toward ensuring identification of the company's full entitlement. The re-measurement of quantities of work and the monetary evaluation of variations issued by a client are generally straightforward. The difficulties arise with

- changes that affect the progress of the work,

- the cumulative effect on the schedule of a number of changes that, individually, may have little or no effect, and
- the introduction of changes late into the schedule.

There is no easy method for identifying or quantifying the above types of changes. However, there are two basic rules that assist in carrying out this identification and qualification:

- Each employee must be fully aware of, and be fully conversant with, their individual scope of work, its budget and schedule, and how their work fits into the overall plan.
- When a change occurs to that scope of work and/or schedule, whatever the cause, then the individual concerned must immediately notify the project manager of change and ensure that its effects are quantified.

In the evaluation of schedule and cost effect of all changes, the following actions will make the task simpler and more productive:

- Identify the change as early as possible;
- notify relevant personnel and/or the client;
- quantify the schedule and cost effects as soon as possible and within a prescribed time;
- keep the client informed of the effects; and,
- request the client's instructions on recovery measures.

1.1.5 Variations and Claims

The quality of the presentation of a variation request, or claim, can have an important bearing on the amount the contractor will be paid.

A sloppy presentation will indicate either lack of knowledge on the subject or lack of confidence in any entitlement to be paid, and it will be treated accordingly by the client. Good presentation will maximize the payment.

The presentation should be well prepared and built up systematically from the contract base, and it should clearly detail all effects of the change. All backup documentation should be clearly referenced and attached to the variation request. It will be much easier to achieve a high-quality presentation if all involved parties pay attention to the actions previously described.

While there is often the temptation to take shortcuts on the preparation of variations, this is usually counterproductive. By good preparation and good presentation, the welding engineer will help the client to pay his company its full entitlement — and on some occasions, perhaps more.

Three main factors therefore emerge, all essential when dealing with commercial aspects:

- Keep good and explicit records,
- be vigilant, and
- think profit.

The foregoing was a general summation of the relevant commercial aspects in which a company welding engineer should be involved during a project. However, there is one very important function in particular that deeply involves this individual — dealing with specifications. Section 1.2 will discuss this aspect in detail. Many other facets also relevant to commercial success — welding costs, choice of equipment and consumables, assessing procedure requirements etc. — are dealt with in subsequent chapters.

1.2 Dealing with Specifications

International codes and specifications often vary with respect to the degree of legal influence they carry. Similar variation exists internationally in the administration of such codes and practices. In some countries there is an inspectorate — that is, a board of inspectors — that makes rulings on the interpretation of the code, approves the design, and carries out physical inspections during construction. In other countries (the U.K., for example) there is no government-approved inspectorate; instead, an independent authority is generally appointed by the purchaser to inspect on their behalf.

In such a disparate legal and political environment, the only safe procedure is to work according to the code specified. However, there is no logical reason why specifications and codes related to welding fabrication should be exempt from rational and critical scrutiny, with the intent of obtaining cost reductions. Of course, the importance of welding to the overall integrity and reliability of a fabricated component must not be understated; but, by the same token, the specified requirements for materials and for finished weldments should not be regarded as sacrosanct edicts carved in stone. This awareness is especially pertinent when considering a client's individual specifications that supplement a national code. Such additional requirements usually come about in one of two ways: from individuals who choose to incorporate certain objectives through personal experience and prejudice; and from a committee seeking to achieve the highest common denominator acceptable to all (i.e., the most rigid interpretation). The cost implications of the second approach are usually severe.

One natural consequence of supplemental contract specifications is that, more often than not, they tend to place overly heavy emphasis on “how-to” rather than simply specifying what is required. In other words, they are not performance driven. If a given material is sufficient to achieve the desired results, then the welding engineer should be allowed to use it, whether it is alloy steel or chewing gum. Ultimately, such an approach could result in a welding specification comprised of just two tables: One

specifying the base material and weld metal properties; the other specifying any non-destructive examination requirements.

Nevertheless, great care must be taken in assessing the implications of any contract specification out of the ordinary. Particularly important is the stage of negotiation at which this assessment is carried out — i.e., has a contract actually been placed, or is it still at the bid stage? If the latter, then mitigating the apprehension of the client must be the foremost consideration. Sound judgment must be used in deciding which contract specifications will have serious cost implications and which are merely advantageous to avoid, but not serious enough to jeopardize a contract award. Two convenient means can be utilized in exercising this determination. These may be labeled *Exceptions to the Specification* and *Clarifications to the Specification*, and they can be easily written directly into the tender. Two other possibilities exist, but these will be explained in more detail later.

Exceptions to Specification

The *Exceptions* category should be avoided if possible, or at least restricted to those few major items where the specification demands are virtually impossible to achieve economically. The reasons for making such exceptions must be clearly identified. A common example would be a requirement to maintain preheat until a certain percentage of the weld volume has been completed. A simple illustration of this would be rolling a tubular section in the manufacture of a pressure vessel or offshore rig. It is very common for the rolling contractor to tack and root weld the longitudinal joint of the rolled cylinder when it is still in the rolls, then to transfer it later to a welding station. Maintenance of preheat throughout this process is not practicable, and abandoning this requirement can be justified based on the success of past practice. Indeed, the argument of successful past practice is a very persuasive one and should be used whenever possible.

Clarifications to Specification

Clarifications to the Specification can be a subtle method of identifying what are really exceptions. These are basically in-house or preferred interpretations of sections of the specification that are unclear or ambiguous. Obviously, the interpretation most practical for the welding engineer will be preferred; but, on occasion, it is advisable for the engineer also to consider foregoing the preferred interpretation and applying the less-convenient one. In the latter instance, when a significant cost can be attributed directly to the client's preferred or anticipated interpretation, then it should be noted specifically in the tender. If the client's perceived benefit does not outweigh the additional cost, then a reversal of opinion will likely be forthcoming.

As mentioned previously, there are two other useful tactics that fall outside of the above classifications. One is to include a passing general statement in the tender that would leave an open door for future compromises on the requirements of the contract.

No client likes to see pages of alteration to his specification, especially if much of it is relatively minor; but a convenient phrase, such as, “there are in addition a number of items on which we would welcome discussion,” can tentatively gloss over an indefinite number of exceptions and clarifications. Further discussion is often delayed until after the contract award; or, alternatively, such discussion can be deferred until the post-contract period and slowly advanced to the client under the guise of engineering queries. Small modifications in the specification to avoid changes in production activities or welding practices can be swept up rather informally by this approach without irritating the client.

In addition, exceptions, clarifications, etc. — although they are common practice — can reflect negatively upon the client; and it may be worthwhile, especially in pre-tender negotiations, to offer options. Although usually designed to suit the fabricator, these options also should convey to the client that acceptance of such will be advantageous to him either technically, economically, or otherwise. Consequently, these should be presented in a logical and structured fashion with client benefits clearly stressed.

Monitoring Production

There is a very common pitfall of which the welding engineer must be ever mindful when dealing with specifications. It is the assumption that his interpretation of a client’s specification, if it is against the company’s practice, will be applied in production when a tender becomes a contract. Ideally, the welding engineer’s responsibilities with respect to specifications will be defined loosely enough to permit his feedback throughout the company’s departmental structure. Generally, it is better (and safer) for the company to allow this sort of follow-through on a contract, rather than assume that it will be covered by some other department.

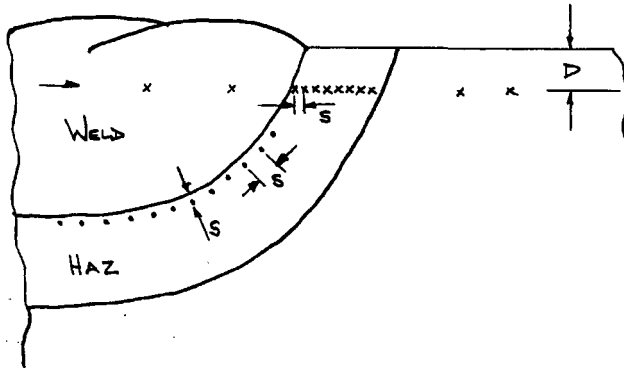
Of course, the responsibility of the welding engineer principally will be with those points in the specification dealing directly with welding activities. However, there can be instances outside of the engineer’s day-to-day responsibilities in which other departments rely on his guidance. If, for example, the engineer is aware of recent changes in welder qualification requirements, it is his obligation to convey this to others, regardless of departmental responsibilities, to ensure that the contract is executed correctly.

In every industrial setting, engineers face process-control problem areas, and the welding engineer is no exception. Therefore, all specifications should be compared to the last contract and examined for changes. Never assume that the specification is identical just because the client is the same. Likewise, never assume that different clients will interpret the same specification in a similar manner.

Examples of such potential problem areas are:

- *Material Weldability* — Is the steel identical to that supplied for the last contract, or should new weldability tests be carried out?





D = Max. depth relative to the surface, typically 1.0, 1.5 or 2.0 mm.

S = Max. space (center to center) between indentations through heat-affected zone (HAZ), typically 0.5 mm or 0.75 mm (may vary with location in survey).

1. The higher the value of S the fewer the indentations made and the less risk of encountering a "hard spot."
2. The value of D will affect different welds in different ways depending on the weld interface shape.
3. Generally higher loads provide an averaging effect and decrease the risk of reporting "hard spots."
4. Some surveys ask for additional impressions (shown as dots above) following the weld interface. This type of survey will increase the risk of reporting high values due to the increase in the number of impressions adjacent to the maximum hardness zone.

FIGURE 1.1 — ASSESSING HARDNESS SURVEY REQUIREMENTS FOR STEEL WELDMENTS

Different manufacturers can supply to the same specification using different routes, resulting in wide weldability differences.

- *Hardness Surveys* — Are the test locations and test loads similar to those previously used? Small changes to these details can change the values obtained. Some typical survey requirements are illustrated in Figure 1.1.
- *Impact Tests* — Are the acceptance values and test locations the same? Are the test temperatures specified the same?

There are numerous other examples, and the welding engineer should, at the very least, draw up a mental checklist of such potential pitfalls.

Having identified the differences, what should be done about them? One option would be simply to identify them as exceptions or clarifications, as shown previous-

ly; but, obviously, it would be better if they were not. A preferable option, if it were possible, would be to carry out in-house testing to ascertain the effects of the change on the cost and time of production. Possible testing methods might include simple repeat hardness surveys, or bead-on-plate trials to examine effect of preheat/hardness levels. These need not be extensive or expensive, but the results can reaffirm confidence in accepting a specification.

A final word of caution is extended here regarding the interpretation of suppliers' typical data (consumable or weldability data, and the like), and the relevance of this data to specification requirements. Do not assume these values are minimum or even average values; in fact, they are more likely to represent typical good results from tests carried out under ideal conditions. In cases where such typical data are close to your minimum specified requirements, take great care to avoid assuming responsibility for aspects of a specification that may prove to be technically unachievable. Such assumptions may lead your company to penalties for failing to attain specified requirements, with all the commercial implications such failures carry.

Chapter 2

Selection of Welding Processes, Equipment and Consumables

In this chapter it has been assumed that the welding engineer has a basic theoretical knowledge of the various welding processes. There are many worthwhile books available on this subject (see recommended reading), so no attempt will be made here to provide detailed information on welding processes. However, as a memory aid, Table 2.1 lists the main processes likely to be encountered. Some of the advantages/disadvantages pertaining to each are also identified.

2.1 Welding Process Selection

The “ideal” welding process is that which achieves the minimum specification requirements at the minimum cost; and, although the selection of a process for a given welding application is seldom scientific or precise, it always requires careful judgment. Moreover, the approach to process selection should be sufficiently thorough to ensure balanced judgment. There are several aspects to be considered, and a careful assessment of each in turn should be undertaken by the welding engineer in close association with production personnel. The main factors to be considered are shown in Table 2.2. These factors address *quality* (a contractual obligation) in conjunction with *resources* and *cost* (both related to profitable operation).

The correct process choice, therefore, is the best compromise between *resources* and *cost*, which also satisfies *quality*. Each of these aspects will now be discussed in more detail, but a summary of the selection method is given in Figure 2.1.

Specification Requirements

The fabrication specification is the first and most important step in selecting a process. At this stage the engineer must establish what is required — in terms of joint type, mechanical properties, nondestructive examination (NDE), etc. — not only for the particular joint in question, but also for the overall effect of welding on tolerances, where these could influence the approach to a particular fabrication problem. Clearly, the specified requirements represent a fixed point in the process selection exercise, and, unlike the many other factors concerned, a compromise is not acceptable in terms of the minimum quality demanded by the specification. Therefore, it is the duty of the welding engineer to ensure the process, or processes, accepted at this initial stage are capable of meeting all specification requirements. A list of typical points for consideration at this stage is given below. These at least should be questioned mentally and assessed by the welding engineer prior to his decision.

FEATURE	ARC PROCESSES						OTHER PROCESSES			KEY
	GTAW	GMAW / FCAW	SMAW	SAW	FCAW-S	ESW	EBW/LASER	RESIST- ANCE	OFW	
PROCESS OPERATION										
AUTOMATION	2/3	3/4	2/3	4	2/3	4	5	5	1	5 - FULLY AUTOMATED, 1 NOT SUITED
ADAPTABILITY/FLEXIBILITY	4/5	3	4/5	2/3	4/5	2	2	2	3	5 - VERY ADAPTABLE, 1 VERY LIMITED
POSITIONAL CAPABILITY	5	5	5	1	5	1	5	5	5	5 - ALL POSITIONAL, 1 LIMITED
USE ON THICK MATERIALS	3	3	3	5	3	5	5(EBW)	1	1	5 - WELL SUITED, 1 NOT SUITED
USE ON THIN MATERIALS	2	3	2	1	2	1	5	5	5	5 - WELL SUITED, 1 NOT SUITED
EASE OF USE (CRAFT SKILL)	3	3	3	1	3	2	1	1	1	5 - MOST DIFFICULT, 1 RELATIVELY EASY
PROCESS COST										
PRODUCTIVITY	3	3/4	3	5	3/4	5	5	5	1	5 - PRODUCTIVE, 1 SLOW
CAPITAL COST	2	3	2	3/4	3	3/4	5	3/5	1	5 - HIGH, 1 LOW
QUALITY OR MATERIAL RELATED FEATURES										
HYDROGEN LEVELS	1	1/2	1	2/3	2/3	2	1	1	1	5 - VERY HIGH, 1 VERY LOW
WELD QUALITY/ INTEGRITY	1/2	2/3	1/2	3/4	3	3	5	1/2	4	5 - HIGHEST, 1 LOWEST
RANGE OF MATERIALS	3	3	3	2	2	1	5	3	3/4	5 - WIDE RANGE, 1 LIMITED
HEAT INPUT	-	3	-	4	1/2	5	-	-	4/5	5 - HIGHEST, 1 LOWEST

NOTE: THE NUMERICAL VALUES GIVEN ABOVE ARE PURELY FOR GENERAL GUIDANCE TO ALLOW A BROAD COMPARISON BETWEEN PROCESSES TO BE MADE. THEY ARE NOT INTENDED AS PROVIDING ANY ACCURATE ASSESSMENT OF PROCESS CAPABILITY.

GTAW = Gas Tungsten Arc Welding; GMAW = Gas Metal Arc Welding; FCAW = Flux Cored Arc Welding; SMAW = Shielded Metal Arc Welding; SAW = Submerged Arc Welding; FCAW-S = Self-Shielded Flux Cored Arc Welding; ESW = Electroslag Welding; EBW = Electron Beam Welding; OFW = Oxyfuel Gas Welding.

TABLE 2.1 — WELDING PROCESSES

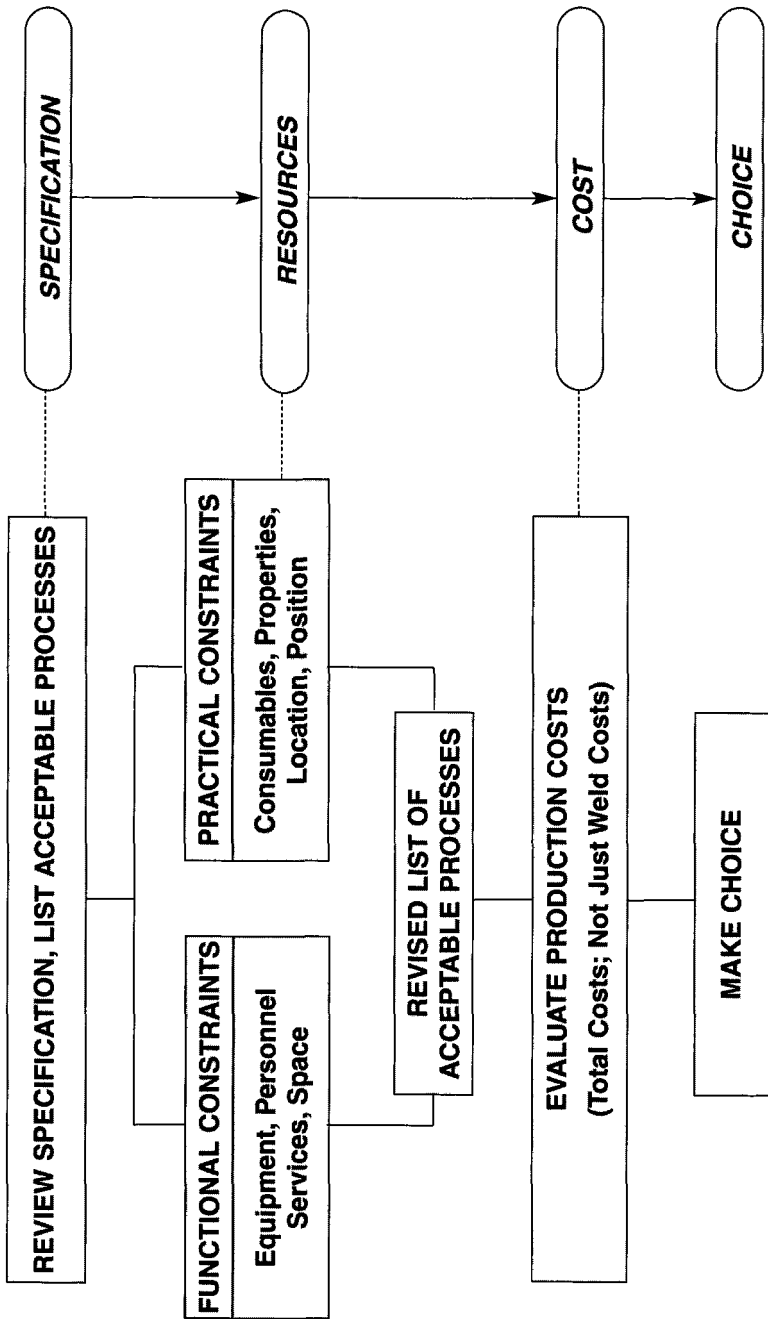


FIGURE 2.1 — PROCESS SELECTION METHOD

- *Mechanical properties*: tensile strength, impact toughness, high/low temperature properties, etc.
- *NDE performance*: visual only vs. volumetric; technique specified, acceptance levels, etc.
- *Special features*: dimensional tolerances, surface finish, etc.
- *Weldability* (i.e., special material requirements): ferrous vs. nonferrous, dissimilar or reactive metal, etc.
- *Limited selection per specification*: Does the specification limit process choice directly? They often do.
- *Consumable availability*: choice limited by availability of suitable consumables

Practical Constraints

Within this category are found the many and varied aspects of a fabrication method that can influence the choice of welding process. It is therefore necessary to establish the overall manufacturing sequence ahead of, or at least in parallel with, any decision on welding methods. For example, the initial selection stage may have identified three processes — shielded metal arc welding (SMAW), flux cored arc welding (FCAW), and submerged arc welding (SAW) — as suitable for a simple fillet weld. Yet, it quickly becomes evident that SAW is not suitable if the component happens to be fabricated in a sequence that places this fillet in, say, the 3G position. The mechanical properties inherent in certain combinations of processes and consumables for various welding positions also must be considered at this stage. For instance, if low-temperature impact properties are not important, then a particular self-shielded FCAW consumable could be used for 3G uphill welding, whereas if impact properties are critical [1], downhill welding or even another process may be required. Other factors — such as accessibility, fitup, type and standard of weld preparation, etc. — can all influence the suitability of the welding process chosen. Similarly, other environmental features such as indoor (shop) vs. outdoor (site or field) fabrication have a major influence on process choice, particularly with respect to the suitability of gas shielded processes.

FACTOR	GOVERNED BY
Quality	Specification
Resources	Practical constraints Functional constraints
Cost	Economic factors

TABLE 2.2 — WELDING PROCESS SELECTION



Functional Constraints

Unlike the previous considerations, this group contains a number of intangible factors as well as tangible and straightforward problems. The more easily recognizable areas to be considered are

- availability of equipment;
- availability of personnel and skills;
- availability of services such as gas, power, water, air, etc.; and,
- availability of shop space.

Each of the above items will influence the choice of welding process — either directly via the total unsuitability of available resources, or indirectly via the additional cost of providing suitable resources. As such, these aspects are dealt with relatively easily during the selection of a welding process. More difficult is the assessment of the sometimes-less-tangible constraints imposed on the selection decision, such as

- utilization of personnel (i.e., if there are a number of skilled welders from another project available on a part-time basis, economic factors may demand the use of such personnel),
- capacity of individual work stations (i.e., there may be existing production bottlenecks to be avoided), and
- overall time savings (i.e., there is little point in welding a component faster unless the total production time is reduced as a result).

Economic Factors

If all other factors are equal, the final choice of welding process should be made on the basis of production costs.

An assessment of costs, however, involves many interrelated factors, some of which already have been mentioned. It is important to consider costs on the basis of *final cost*, not on the basis of individual process costs in isolation. Thus, if a group of skilled shielded metal arc welders were available for an average of 10 hours per week (surplus to the requirements of another project), then it may be worthwhile to utilize SMAW for a particular application rather than the nominally more productive FCAW or SAW.

Similarly, it may prove more economic to choose a less productive welding process to achieve some other desired feature (e.g., surface finish), where the additional time spent welding the component can benefit overall production costs by reducing machining or dressing operations later. Careful consideration should also be given to the merits of mechanization or automation; since, despite the major productivity benefits, the potential payback is highly dependent upon the degree of utilization in the plant. As a result, what may be a good investment in a production line environment (high utiliza-

tion) may prove excessively expensive in a mixed fabrication shop (low utilization), despite any improvement in the welding time for the item in question.

2.2 Equipment and Consumable Evaluation

General Principles

The evaluation of new equipment, or alternative consumables, can sometimes form a significant part of the welding engineer's function, although this obviously depends on the type of business in which the engineer is employed and, in some cases, only if sufficient time is available. Nevertheless the importance of a good evaluation system should be recognized by all. As a starting point, the following questions should be posed:

- Why is the proposed evaluation being carried out?
- What are the key points of interest?

If the answer to either of the above cannot be identified positively, then it is likely that the proposed evaluation is either premature or unnecessary, and of little benefit to you. It is very important to identify in advance the main factors of interest and not allow good salesmanship by your supplier to lead you into receiving a demonstration of only the best features of the equipment or consumable. These are of little value unless they are also what you require. Another point worth remembering is that by the time your evaluation is complete and your "technical" choice has been made, it may then be too late to obtain the best commercial deal with your supplier. It is therefore a good general practice to obtain quotations or pricing information at an early stage, particularly in situations where competitive products are being assessed.

For both consumables and equipment, there are two general reasons leading to a need for assessing new or alternative products, namely,

- alteration of existing practice, e.g., replacement plant or consumables, and
- introduction of new practices, e.g., replacement of SMAW by semi-automatic welding.

Each of the above require a different treatment. In the first case, where there will be no change in working practices, the comparison to be made should be straightforward. Here, existing equipment and consumables will form a benchmark against which the performance of the new product can be measured. It is still important, however, to approach the evaluation methodically. For this reason a checklist, or score sheet of some form, can introduce a degree of objectivity. This aspect will be discussed in more detail later. In the second case, the evaluation can be twofold in that the equipment and consumables are not only being evaluated against competitive products, but also against existing practice in terms of productivity, NDE performance, etc. This situation can lead to problems, and it is better to keep both of these aspects separate. Although this may be difficult, it is important to avoid situations where a product is being condemned on the basis of a requirement related to an existing practice, which

may not be relevant if the overall working practices are changed. There is no doubting the fact that the availability of capable welding equipment and consumables will affect the decision-making process in relation to changing working practices. However, unless only one specific consumable or piece of equipment is potentially suitable, the process decision can be made based on generic information. Having made the decision in principle to change working practice, then the equipment or consumable assessment can be carried out against clearly defined target requirements.

Equipment Assessment

As mentioned above, it is worthwhile to establish a checklist against which both your requirements and equipment performance can be judged. This will differ, obviously, for different types of equipment; nevertheless, the following lists are offered as examples dealing with two distinct applications.

Power Source Checklist

- Type of current (AC or DC).
- Polarity (electrode positive or negative).
- Pulsing facilities (peak current range, background current range, frequency range, synergic capability).
- Programmability (e.g., preset facilities).
- Process capability (Shielded metal arc, submerged arc, gas metal arc [GMA], flux cored arc, and gas tungsten arc welding [GTAW]).
- Interchangability with existing plant (e.g. spares).
- Power input requirements (power limitations, single-phase, three-phase, type and availability of fuel for generator engine).
- Energy consumption (i.e. efficiency).
- Duty cycle.
- Ancillary equipment required (wire feeders, high frequency units, etc.).
- Availability, cost, and ease of servicing.

Orbital Gas Tungsten Arc Welding Unit Checklist

- Type of head (direct pipe mounting vs. track mounting).
- Power source and programmer (pulsing mechanisms, programming systems, level and number of programming steps possible for given current, voltages, wire speed, travel speed).
- Pipe size capacity.
- Ability for interchange of heads.
- Head facilities (wire positioning facility, wire drive on head, external arc-length or arc-voltage control, gas lens, water-cooling facilities, electrical and thermal protection, general ruggedness).
- Head access limitations.

- Length of interconnects.
- Number of passes possible on continuous operation.
- Head/track clamping methods (i.e., automatic vs. manual centering, arc voltage/length monitoring mechanisms, etc.).
- Previous industrial experience.
- Availability, cost, and ease of servicing.
- Availability of machining facilities for weld preparation.
- Necessity for orbital welding (possible options such as rotation of component, etc.).

The above examples are intended to illustrate the advisability of an objective approach to equipment assessment and purchase; they should not be regarded as ideal checklists. The ideal checklist is the one outlining your requirements in detail.

Consumable Assessment

The selection and assessment of consumables depends very much on the application range in view. For instance, there is little value in assessing the positional welding capability of a filler metal if the intended use is exclusively for flat-welding-position fillets. Obviously, there is a need to match the assessment to the application. Having established the target application(s), the assessment of any consumable provides two main areas for evaluation, namely,

- operability, and
- weld properties.

Each of the above features is examined differently — that is, “operability” is a judgment affected by the welder’s ability and bias, whereas “weld properties” normally will present a well defined target that may or may not be achieved. The only complication regarding weld properties is that these are influenced by the detailed weld procedure used. It is recommended, therefore, that you incorporate the recommendations of the consumable manufacturer regarding specific techniques in any evaluation involving a property assessment. If these recommendations are impractical, or limiting (but necessary), then this factor in itself could eliminate a consumable from further consideration.

Operability, however, is of equal importance; there is much to be said for a product that has “welder appeal.” Ease of use normally will translate into fewer defects and better productivity, so operability should be an important consideration in any evaluation. Given that operability can be a subjective assessment, it is worthwhile to establish a score sheet covering the various aspects of operability that should be addressed. An example of such a score sheet is shown in Figure 2.2. This is a particularly useful tool when evaluating manual-process consumables. Another consideration is to hear reactions from several welders, because opinions often vary. In terms of general approach, the first action would be to identify a number of consumables that meet the mechanical and chemical analysis requirements of the weld “on paper.” Having estab-

CONSUMABLE ASSESSMENT SHEET

Electrode:	Welding Current: DC ☐ AC ☐ Amp:
Power Source:	Special Tests:
Joint Prep:	Welder:
Welding Position:	Date:

EVALUATION OF WELDING CHARACTERISTICS

	Score*	Comment
Arc Action:		
Striking/Re-Striking	☐	
Weld Root Stability	☐	
Fill & Cap Pass Stability	☐	
Slag Action:		
Control	☐	
Removal	☐	
Fume Emission	☐	
Coating Stability	☐	
Deposit:		
Shape/Profile	☐	
Spatter	☐	
Total:	☐	

General Comments: _____

*Scale: 10 = Excellent 8–9 = Above Average 6–7 = Average 0–5 = Below Average

FIGURE 2.2 — SAMPLE SCORE SHEET FOR CONSUMABLE ASSESSMENT

lished such a list, samples can be obtained and used for simple operability tests. These should be designed to suit your intended application (e.g., for SMAW on a fully positional pipe weld using a butt joint, a simple test involving the filling of a shallow groove in a 5G- or 6G-positioned pipe would suffice).

The best two or three products can then be assessed further on the basis of full weld procedure tests to establish required properties. The “operability” factor obviously can mean different things for different processes; examples of what *should* be considered for shielded metal arc welding are given below:

- Deposition efficiency.
- Coating type (basic, rutile, iron powder, etc. — choices may be limited by specification).
- Electrode application range (current and polarity, positional limitations per available resources and applications, etc.).
- Electrode operability (factors to be considered and “scored” include arc action [striking/restriking, root stability, and the stability of the cap pass]; slag action [control, removal, fume emission, coating stability, etc.]; and deposit [shape and spatter]).

An example of an evaluation code that incorporates many of these features in greater detail is shown in Figure 2.3.

For processes employing a bare wire electrode, there is seldom a need for an “operability” type of assessment on the wire consumable, since these usually are ordered according to an analysis specification. Other processes, especially those that involve a flux, can be treated in a fashion similar to the SMAW scenario described above. For all welding processes, including SMAW, a further consideration in many industries is the level and type of consumable-handling practices required to meet and maintain low weld-metal hydrogen values. As this can have cost implications and affect the preheat levels required, it is a factor that also must be considered before the final choice of a consumable.

References

- [1] Rodgers, K. J., and Lochhead, J. C. 1987. “Self shielded flux cored arc welding — the route to good toughness.” *Welding Journal* 66(7): 49–59.

EVALUATION CODE FOR TEST WELDING

SLAG REMOVAL

1. Slag very difficult to remove.
2. Slag difficult to remove
3. Slag cover is whole and remains on bead but can be removed with normal de-slagging method for the type of electrode, i.e., wire brushing, use of chipping hammer, etc.
4. Slag cover remains on bead but is loosened up by cross cracking and is easy to remove.
5. Slag is self-releasing.

Auxiliary Code

SS Large areas of slag remain on bead after de-slagging.

S Small areas of slag remain on bead after de-slagging.

Sp Slag particles "fly off" during cooling.

h addition to 4 if the slag loosens in one piece with light de-slagging.

+ used when comparing two electrodes where the difference between them is not great enough to shift from one main code to another.

SPATTER

1. More spatter than normal for the type of electrode.
2. Normal spatter.
3. Less spatter than normal for the type of electrode.

Note: The above may be augmented by a "+" to differentiate small differences between two electrodes.

ARC STABILITY

1. Less stable than normal for the type of electrode.
2. Normal stability
3. More stable than normal for the type of electrode.

Note: The above may be augmented by "+s" if there is a tendency for the arc to extinguish, or "+n" if there is a tendency for the electrode to "stick" or "freeze."

OVERHEATING

Any overheating tendency is shown by indicating approximately how many mm of the electrode remains at the point when overheating effects are noticed.

WELD BEAD APPEARANCE

Two numbers are used here. The first describes bead shape in a V-Joint as follows:

- 1 Convex (high peaks)
- 2 Convex (very high peaks)
3. Flat
4. Concave

A second number is used to describe bead surface smoothness (i.e., solidification ripple pattern) as follows:

1. Ripples coarser than normal for the electrode type.
2. Normal ripple pattern.
3. Ripples finer than normal for the electrode type.

Note: An additional "+" may be added to differentiate between two relatively close electrodes.

COATING BRITTLINESS

The electrode is bent over a 150-mm-diameter pipe, and a scale of 1-5 is used to describe the effect on the coating.

1 = very brittle 5 = very ductile

RE-STRIKING

For those electrode types where this property is of interest, restriking is tried 5, 10, and 30 seconds after the arc is extinguished. Welding time before the arc is extinguished is about 10 seconds. If the electrode re-strikes then the appropriate box is marked with X.

COMMENTS

Any special observations are noted here, e.g., porosity, slag removal on root side, if electrode gives unusually much or little fume, if the coating breaks off around the arc, if the slag characteristics change during a test series run, if the arc column is stable in the joint, etc.

FIGURE 2.3 — SAMPLE EVALUATION CODE

Chapter 3

Weld Procedure Qualification

A major part of any welding engineer's job is the assessment, initiation, qualification, and reporting of weld procedure tests, and the engineer's performance in this area has considerable financial implications. Significant cost penalties can result if he should fail to identify completely the specified requirement, choose consumables that prove inadequate for the function intended, or fall short of completing the proposed weld procedure qualifications within the production program requirements. The following sections discuss various finite stages to be observed during the welding procedure qualification process.

3.1 Assessing Weld Procedure Requirements

During the bidding or pre-contract stage, drawings and specifications must be examined carefully to assess the number of tests that will be required, taking into consideration the thickness ranges, the material groupings, the heat treatment conditions, and the welding positions. If there is sufficient time, this initial assessment should be circulated among managers in other appropriate disciplines — such as planning, quality assurance, and, especially, production — for comment and feedback. Cognizance should be taken of any restricted-access conditions or equipment limitations; and, where necessary, alternative procedures should be proposed. Insomuch as an initial procedure-requirement estimate is seldom sufficient to accommodate client alterations, changes in fabrication methods, and other unforeseen factors, it is a good rule of thumb to overestimate by 10 percent when establishing budget requirements. Of course, this “contingency multiplier” could be increased or reduced depending on the engineer's level of confidence in, or familiarity with, the type of work being bid.

Having established the initial procedure test requirements, the engineer preparing the bid should determine whether any of the proposed procedures can be considered suitable for acceptance by virtue of being “prequalified.” Confusion can arise between the casual use of the terms “prequalified” and “previously qualified.” A prequalified welding procedure specification is defined in ANSI/AWS A3.0-94 — *Standard Welding Terms and Definitions* as “a welding procedure that complies with the stipulated conditions of a particular code or specification and is therefore acceptable for use under that code or specification without a requirement for *qualification testing*.” (author's emphasis).

In some cases, prequalification may relate to the use of code-approved procedures (e.g., AWS D1.1), but it can equally relate to situations where previously qualified procedures (satisfying all current requirements) are the only allowable means of pre-

qualification. This assumes, naturally, that the relevant national or client specification permits prequalification, and that the proposed material is sufficiently similar to that on which the previous tests were performed. Even so, the engineer might consider testing a limited number of specimens to reassure both himself and the client that the materials are worthy of prequalification. Qualification is a significant factor in the cost of most fabrications; therefore, one must take advantage of prequalification whenever permissible. This is why engineers often will specify a desired procedure in terms of more than one process, each of which is prequalified separately; or, they will combine the results of several procedures into a single “hybrid” procedure, which can then be offered (with supporting data) for consideration by the client as being prequalified.

At this point, one could deliberate the extent to which the engineer may apply the strategy of substituting specified procedures with prequalified procedures. For instance, it may be that certain specified procedures differ from existing qualified procedures in only minor details — e.g., number of specimens, location of hardness tests, etc. Should the prequalified procedure be discounted? — not necessarily! In the interest of cost reduction, many clients will accept such procedures, especially if the rest are qualified as originally specified. However, the engineer must have enough familiarity with the client to win his confidence, as this action presumes a good deal of faith in the engineer’s judgement. Offering alternatives is an easy way to avoid cost-inflating specification details, particularly when they impact procedure qualification requirements. The engineer can always offer a small amount of additional testing once the bid is accepted. This can be a useful tactic in persuading the client to accept his recommendations.

Finally, when the information at hand is inadequate to fully establish welding procedure requirements, the welding engineer must be prepared to recognize this during the bidding or pre-contract stage. Two strategies are available to the engineer in this event. First, he can assume, from background knowledge and experience, what type and number of procedure tests are likely to be required; then, these can be listed and identified to the prospective client as the total number upon which the price has been established. Second, an average price per individual test plate can be calculated; this figure can then be inserted into the bid document, leaving the final price subject to change. Most clients favor the former method, not surprisingly, as they prefer to have at least some knowledge of what the ultimate figure will be.

Planning a Test Program

At this stage, the number of prequalified procedures should be removed from the pre-contract list of procedures to be tested, and the welding engineer should subsequently engage other departments, as necessary, in the preparation of a qualification test program. Priorities must be established as early as possible so that the required procedure will be qualified, reported, and accepted by the client as far in advance of the production starting date as possible. Seldom will a program run 100-percent smoothly; so, a time cushion should be included to allow for possible rewelding due

PROCEDURE NO.	PROCESS	POSITION	MATERIAL	JOINT TYPE/ APPLICATION	HEAT TREATMENT	MATERIAL THICKNESS RANGE	PRE-QUALIFICATION
21	SAW-SINGLE	1G	C-STEEL	V - PLATE BUTTS	AS WELDED	15-40	TO TEST
22	SAW-TANDEM	1G	C-STEEL	V - PLATE BUTTS	PWHT	40-70	TO TEST
23	SAW-SINGLE	2F	C-STEEL	FILLET - BEAMS	AS WELDED	15-30	TO TEST
24	SMAW	5G	C-STEEL	V - PLATE BUTTS	AS WELDED	20-35	TO TEST
25	SMAW	3G	C-STEEL	V - PLATE BUTTS	AS WELDED & PWHT	15-40	TO TEST
26	SMAW	1,2,3,4F	C-STEEL	FILLETS GENERAL	AS WELDED & PWHT	15-40	REFER PROC. NOS. 4, 5, & 6
27	GTAW	5G	316 STAINLESS	V - PIPE BUTTS	AS WELDED	2-6	REFER PROC. NO. 12
28	GTAW	5G	CUPRO-NICKEL	V - PIPE BUTTS	AS-WELDED	2-4	TO TEST

SAW= Submerged Arc Welding; SMAW = Shielded Metal Arc Welding; GTAW = Gas Tungsten Arc Welding; PWHT = Postweld Heat Treatment

FIGURE 3.1 — A TYPICAL WELD PROCEDURE SUMMARY SHEET

to nondestructive examination (NDE) or mechanical test failures. Regardless of the number of times a procedure has performed satisfactorily in the past, statistical laws guarantee that there will be a failed result eventually, and Murphy's Law guarantees this result will occur at a critical time. Figure 3.1 illustrates a typical weld procedure summary sheet identifying most of the relevant points mentioned in this section.

Assessing Test Material Costs

The quantity of material required must be considered carefully, since additional costs can result from underestimation as well as overestimation. A modest overestimate, however, is preferable to an underestimate that results in embarrassing program delays. The foremost requirement is to provide sufficient test material for conducting all required mechanical tests plus an allowance for retests. The importance of this extra allowance should not be discounted, as there are few experiences more frustrating than having to rerun entire procedure tests for lack of a few extra millimeters in the original test piece.

In estimating the amount of weld required for mechanical test purposes, it is necessary not only to list the number of tests to be taken (making an allowance for retests), but also to identify the amount of material required per individual test piece. Also allow for the wastage of material due to machining or cutting. This issue is best discussed in advance with the testing facility performing the mechanical tests; the testing facility can often provide useful guidance on overall material requirements for individual weld procedure tests. As a simple illustration, consider the following cases:

- A pipe butt joint weld procedure qualification on small-bore pipe (say, 1 in. [25 mm] or less) — here, several individual butt joint welds may be required to obtain the tests needed for one weld procedure qualification.
- A thick plate (say, 2 in. [50 mm] or greater) butt joint weld involving Charpy impact testing at several locations. In this case, impact specimens for weld root, mid-thickness and the cap pass subsurface usually can be machined from a single through-thickness slice at a particular location; hence, the total length of weld required may be less than for some thinner plates.

The importance of having some spare procedure test material should not be ignored; but the cost of providing redundant test samples must be taken into account as well, since the cost of a procedure test program can quickly escalate. Remember that the largest single expense item in a welding test program is often not the material, but labor. If all procedures in a weld procedure qualification program were based on manual welding processes (e.g., shielded metal arc welding [SMAW]), any major over-allowance on the amount of weld required could prove very costly. Conversely, for automatic and mechanized welding (e.g., submerged arc welding [SAW]) the cost of welding a 6-ft-long (2-m) test plate may not be significantly higher than welding a 3-ft (1-m) test plate; and, in this case, a provision for additional test material would be relatively inexpensive. In all cases, a common-sense approach should prevail. A

10- or 20-percent allowance for potential retests should be adequate for all but the most problematic of procedure tests.

Making the Test Welds

Once the procedure test requirements are established, the material identified and sourced, and the test program finalized, then actual welding of test samples can begin. The foremost consideration here is that qualification of procedures should simulate the actual site conditions as closely as possible, using production equipment and production welders whenever and wherever circumstances permit. There is no benefit in qualifying a test piece under ideal conditions, using specially trained welders with better-than-normal equipment. This will only invite trouble later, in production — when welds are rejected during inspection or, worse, when they fail during mechanical testing. Welding parameters used during procedure qualification should be logged for every pass, so that the subsequent welding procedure instruction or operating sheet may be derived based on realistic working ranges for the main parameters.

The importance of simulating production conditions may seem obvious, but it is not always observed in practice. Consider, for example, the use of a temper bead technique to obtain acceptable heat-affected zone (HAZ) hardness levels in alloy steels. While this can be achieved under strictly controlled conditions (such as during a procedure test), it is often impossible to guarantee — or even measure — in a production environment, unless extensive provisions are made to supervise the operation. If specifically required for particular applications, any cap-pass sequence method to be used should be clearly stated and agreed upon with the client. Figure 3.2 illustrates the difference between a true temper-bead technique and a simple, controlled cap-pass sequence. The latter method, although sometimes effective in reducing HAZ hardnesses, cannot be relied

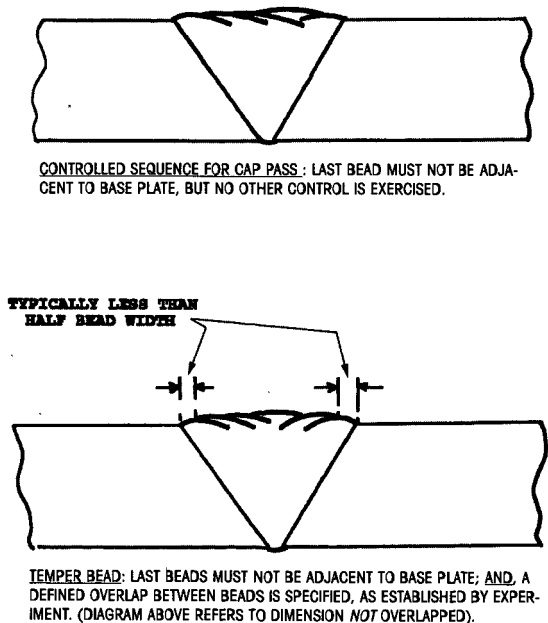


FIGURE 3.2 — COMPARISON BETWEEN CONTROLLED CAP-PASS SEQUENCE AND TEMPER BEAD TECHNIQUE

upon in this capacity unless subjected to the level of control inherent in true temper-bead techniques.

On completion of its welding, and prior to being machined for test purposes, the test plate should be subjected to the same NDE, heat treatment, and other postweld operations planned for the production welds. If the weld fails at this stage (i.e., after NDE), any further action should be confirmed between the welding engineer and the client. It may be still possible to utilize the test plate if the defects found were welder-induced and unlikely to affect mechanical performance of the joint. Otherwise, a new procedure test may be required. In this case, however, the cause of the original NDE failure should be considered; and, if appropriate, the procedure should be changed prior to rewelding.

3.2 Routine Mechanical Tests

The extent of mechanical testing during procedure qualification will depend on the particular application, the appropriate national standards, client specifications, etc. This section is intended to provide an overview of mechanical testing, its relevance, and control. No attempt will be made to discuss specific standards or to provide detailed test methodology. Rather, the more common weld procedure test requirements will be examined, and a number of simple checks will be recommended for use by the welding engineer in assessing both test-house capability and test results. A key point is that all unusual results should be queried (if only mentally), as it is from such results that most experience is gained. Such queries often can lead to a potential production problem being identified at an early stage, and consequently prevented.

Macro-Examination

The purpose of a macro-specimen is twofold: to provide an overall view of the metallographic appearance of a weld, and to provide a cross section that can be examined for weld defects, etc. This specimen can be either a section that samples the weld in a typical or pre-specified location, or a section taken to investigate some particular problem or aspect of the weldment.

Given the considerable amount of information that can be gained from simple macro-examination of a weld, one must question why the humble “macro” is so often underrated. With a detailed knowledge of the welding process, one can gain from the macro-specimen a means of establishing whether or not the weld was completed within the stated parameters. An example of such a use is given in Chapter 4.

In addition, a simple bead count and bead placement check can quickly establish the accuracy of the written weld record for the procedure test in question. In production tests, placing a limit on the total number of beads, or the bead count per unit length of the weld interface, can help ensure that production welds are comparable to procedure test welds.

Aside from the merits of macro-examination, remember that this method is intended to be performed with minimal, if any, optical magnification (commonly x10–x20 maximum), and care should be taken in assessing any apparent defects discovered at higher magnifications. Also, if a specification requires examination at a particular magnification, use it.

Hardness Survey

A hardness survey, normally performed on the specimen taken for macro-examination, is a common requirement of weld procedure tests. The function served by the hardness survey will vary according to the application. Probably the most widely known application relates to identifying the maximum HAZ hardness in structural/pipe steels, as this is regarded as a good indicator of the risk of encountering HAZ hydrogen cracking. In other applications, such as hardfacing, the hardness survey is important with respect to wear resistance; and, in this case, minimum hardness criteria will be specified.

In terms of testing technique, the three main factors to be aware of are choice of load (commonly, Vickers Diamond 10-kg load is specified), calibration of equipment, and accuracy of placement for indentations. The last-mentioned factor is particularly important with respect to many steel fabrication specifications in which keeping below the maximum HAZ hardness is the main objective. Here, indentations are required to be within, say, 0.5 mm of the weld interface and positioned at intervals of 0.5 mm on a traverse through the HAZ. This requires accurate placement of the indentations; and, as this can have a marked influence on the results obtained, the indentation location should always be checked in such cases, with particular attention paid to any unusually low hardness values reported. For most structural steel applications, a macro-specimen employing a Nital (i.e., 10- to 20-percent Nitric acid in Methanol) etch is a long-established and normally acceptable practice for delineating the weld zones. However, some specifications call for the use of dendritic etches using, for example, a saturated solution of picric acid with a wetting agent (SASPA-NANSA), which delineate the fusion boundary more clearly, and also assist in locating the hardness indentation. The relative appearance of both types of etches on similar steel weld samples is shown in Figures 3.3(a) and 3.3(b), respectively. The use of such special etches should be governed by need rather than routine, since they require a considerably better standard of preparation (typically polished to a 1-micron finish) and therefore involve more time and cost. In addition, the SASPA-NANSA etch has been found to be unsuccessful when examining some self-shielded flux cored arc welds.

On some materials, such as certain stainless steels and nickel alloys, the sample preparation can influence the result obtained in a hardness survey due to the formation of a work-hardened surface layer. Awareness of this probability should govern any assessment of unusually high hardness values reported in these materials. Also, on these materials, avoid severe preparation methods such as heavy grinding or milling. It is best to prepare samples by progressive, light surface-grinding passes

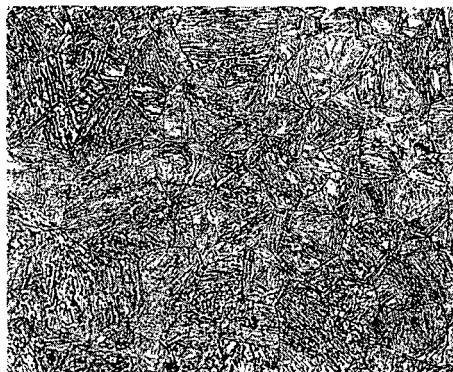
directly on the as-cut surface of the specimen. Although time-consuming, this method is usually successful; if not, the use of other methods, such as electrolytic techniques, may be worthwhile considering.

On some types of welds, particularly single-pass welds in steel, it is possible to get significant hardness variations along the length of the test piece; this is probably due to slight variations in heat input, heat buildup, etc. In such cases, higher hardness values are often found near the start of the weld. In these circumstances, use additional sampling for information purposes — particularly in a situation where the maximum hardness levels reported are approaching any specified limits.

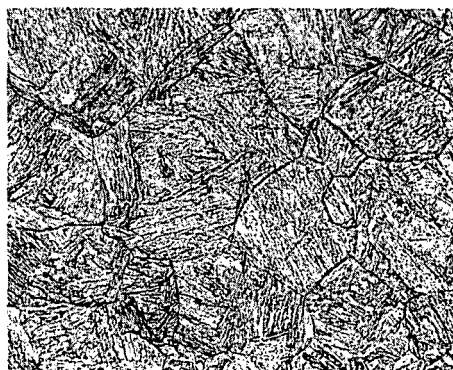
Micro-Examination

Micro-examination is rarely a requirement in weld procedure tests, except in cases where it can influence the serviceability of a component, and where discontinuities must be detected prior to their effect being noticed via other, more routine tests. Micro-examination procedures may include ferrite testing — that is, measuring ferrite levels, which are known to affect solidification cracking, sigmatization potential, and corrosion properties in some stainless steels. Corrosion resistance testing is an alternative, non-optical form of micro-examination.

As with macro-examination, micro-examination should be carried out only after the specimen has been correctly prepared, and always at an appropriate magnification. The information that a micro-examination can provide for the welding engineer is more likely to be worthwhile in situations such as failure investigations, investigations of poor mechanical test performance, etc. — where a detailed metallurgical assessment of the weld and HAZ is often invaluable.



Nital Etch (HAZ Region)
x 500
(a)



SASPA-NANSA (HAZ Region)
x 500
(b)

**FIGURE 3.3 – ETCHES OF SIMILAR STEEL
WELD METALS**

Tensile Testing

The type of tensile test specimens used are variable and are normally governed by the application of a national standard or client specification. Within the scope of weld procedure testing, these fall into two main categories, namely,

- all-weld tensile tests (those in which only the weld metal is tested), and
- transverse or cross-weld tensile tests (those in which the complete weld cross section, including adjacent base material, is tested).

The significance of the tensile test is readily apparent, inasmuch as the information generated has a specific design relevance to the strength of a component or structure. By pointing out this relevance, it is sometimes possible to have results that are slightly outside of specification accepted — presuming, of course, that one checks with the design or structural engineer responsible. Often, the tensile test performance is predictable, and any sudden departure from expected results is worthy of investigation. For instance, an unusually high or low result could indicate a problem with material, specimen location, specimen identification, etc.; such factors should be checked before retesting.

The specimen location within a weld can influence tensile values obtained as a result of dilution effects on the weld metal analysis. This is demonstrated in Figure 3.4, which shows the effect of specimen type/location on results obtained in a typical structural-steel weld. In the case illustrated in diagram (a), the all-weld tensile result is shown to be affected by its “through thickness” location. This is associated with small, compositional differences between the sample close to the root (more dilution) and the sample close to the final layer of the weld (less dilution).

Diagram (b) shows a similar example taken from an actual procedure test. Here, because of the limited capacity of tensile testing equipment, the initial transverse tensile test was carried out as a series of overlapping specimens (an acceptable practice). The results obtained were marginally outside of the specified minimum ultimate tensile strength (UTS) and therefore deemed unacceptable by the client. Then, it was noted that previous all-weld tests performed on the same weld were acceptable, and that the transverse sample taken toward the root side of the weld was also acceptable. For the retest of this weld, it was decided to have a full-section tensile test performed at a different test establishment — where machine capacity was not a factor, and a fully acceptable retest could be obtained. This example is worth remembering, particularly when, as in this case, it is known that the weld metal strength is marginal. In general, the use of a full-size specimen should be beneficial in such situations.

Another test result warranting caution would be any unexpected increase in the yield stress or yield stress/UTS ratio. Again, this could be indicative of a material problem or simply an error in calculation; but, it could be the result of incidental cold work due to improper handling of the test material. An example of the effect of previous cold work, or pre-straining, is shown in Table 3.1.

Yet another notable tensile-test feature in steel weldments would be the appearance of “fish eyes” on the fracture surface, as shown in Figure 3.5. Attributed to the presence of hydrogen, these are sometimes noted on welds made with cellulosic/rutile SMAW electrodes. They also occur occasionally on some self-shielded flux cored arc welds, particularly if tested in as-welded conditions. They should not be considered as defects; but, if noted on welds made with a low-hydrogen process, they are worthy of investigation (e.g., verifying that correct consumables were used).

Bend Testing

Bend tests are essentially qualitative in nature, and so they do not generate data of direct relevance in engineering terms. The bend test is, however, a widely specified (and cheap) test — both as a part of weld procedure qualification and, more often, as a requirement in welder qualification tests. Although crude, the bend test is good at

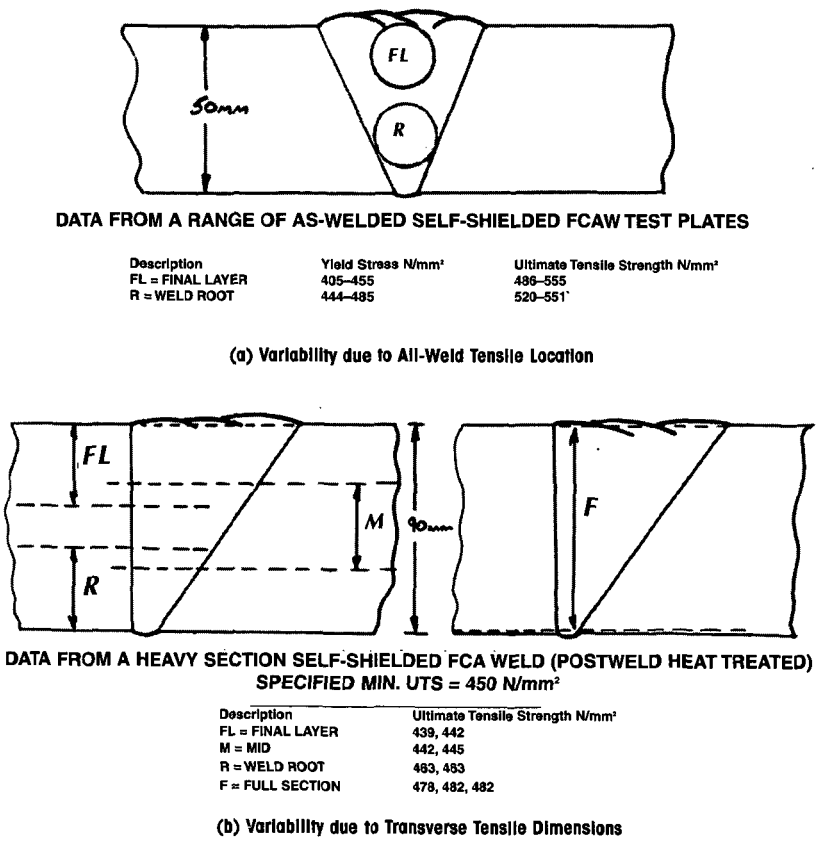


FIGURE 3.4 – EFFECT OF TENSILE TEST SPECIMEN TYPE AND LOCATION

highlighting the presence of weld defects, and it gives a general indication of weld metal ductility.

One situation where more care is required is that involving a weld metal significantly overmatched or under-matched in tensile strength compared to the base material, and similarly for transition welds involving quite different materials. Such situations can have the effect of concentrating the strain in the

lower strength zone, resulting in a failure not necessarily indicative of poor practice. In the former case (weld metal), the preferred solution would be to select a weld consumable more closely matched in tensility. In the latter case, a slight offset of the fulcrum position can sometimes provide a more representative test.



FIGURE 3.5 — EXAMPLE OF "FISH EYES"

Impact Testing (e.g., Charpy Tests)

The impact test, particularly the Charpy V-notch test, is widely used in materials where toughness properties are important. In structural steels, the test is usually carried out at a specified temperature, often -40°C or $^{\circ}\text{F}$; and it provides useful (although only comparative) data on the fracture toughness of the material tested. Unlike the crack tip opening displacement (CTOD) test, which is conducted to provide a direct measurement of fracture toughness, the impact test does not provide a value of direct engineering significance; rather, it produces a relatively cheap and simple way by which materials can be compared against each other over a range of temperatures. After impact testing, and by comparison against historical data, the material can be judged as safe, or otherwise, in terms of fracture toughness.

CONDITION	YIELD STRESS N/MM ²	UTS N/MM ²	YS/UTS
As Received (AR)	363	536	0.68
AR + 2% Pre-Strain	406	553	0.73
AR + 5% Pre-Strain	500	569	0.88
AR + 10% Pre-Strain	583	608	0.96

TABLE 3.1— EFFECT OF PREVIOUS COLD WORK

In weld procedure tests on steels, it is normal practice to test both the weld metal and the heat-affected zone. In the latter case, the positioning of the notch is important; and, close attention must be paid to this point, as moving the notch by as little as 0.5 mm can often have a dramatic effect on the results obtained. Therefore, the notch locations should be checked by etching individual specimens to ensure that the correct locations have been taken. A similar procedure should be adopted prior to notching Charpy specimens to ensure correct notch location. Notch profile and test temperature also must be closely controlled. Despite its simplicity, the Charpy test is one that requires close attention to detail in order to achieve reliable results. Otherwise, the unpredictability associated with impact testing of welds (particularly HAZs) will be so chronic, it will leave the welding engineer seeking divine intervention.

3.3 Simple Checks

Any test performed is of little value if the competence of the testing facility (whether in-house or independent) is questioned. The welding engineer may sometimes be in a situation where a review or witnessing of weld procedure tests is required, possibly at a subcontractor’s premises. In such a situation, the simple checks mentioned in Table 3.2 can be useful for establishing a good level of confidence in the tests being undertaken.

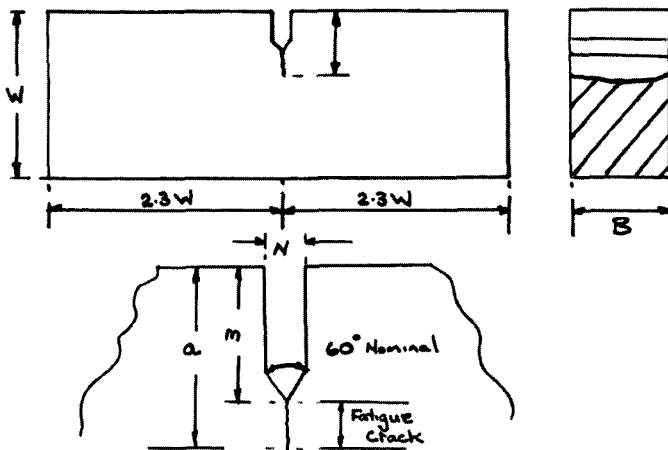
Subject	Check
Equipment Calibration	Verify that all pieces of equipment are uniquely identified and traceable to current calibration certificates.
Test Piece Identification	Verify how incoming test pieces are identified, and that identification is maintained during machining.
Recording of Results	Verify that all relevant data <i>are</i> recorded, and are previous data retrievable?
Tensile Tests	Spot check dimensions, particularly those relevant to cross section.
Impact Tests	Spot check notch profile and review methods used by test house. Check machine zero and specimen alignment. Also check bath temperature (where applicable) just before and/or during testing.
Micro/Macro-Examination	Check that a representative sample has been taken. Verify that macro corresponds to weld records, and check opposite (unprepared) face for obvious defects.
Hardness Survey	Check indentation locations. Also check load used.
Results	Query any unusual results (see previous text).

TABLE 3.2 — SIMPLE CHECKS

The checks presented in Table 3.2 are not intended to provide the requirements for a comprehensive quality or technical audit of a testing establishment; rather, they are provided so the welding engineer may conduct checks at an individual level, easily and informally. Any grossly unacceptable practice highlighted by such checks would, however, warrant a much more detailed assessment under formal guidelines.

3.4 Fracture Mechanics Test

The tests noted thus far in this chapter form a basis for routine weld procedure qualification testing in most industrial fields and have been the norm for many years. However, in some situations (e.g., nuclear industry, offshore structural fabrication, pressure vessel fabrication, etc.) there is an increasing demand for more data on fracture toughness properties — enough so that full consideration of fracture safety can be built into the design of a structure at an early stage. The Charpy impact test, as already discussed, is an excellent “comparator” in terms of fracture toughness; however, this test does not provide data of direct engineering relevance in terms useful to the designer. For data that can be used in such a manner, the crack tip opening displacement (CTOD) test must be carried out (usually at the design minimum temperature). In extreme cases, full-scale load-to-fracture testing or wide-plate fracture toughness testing may be required. The CTOD test is, however, the test most widely applied to welds. This test is fully



Dimension	Standard Specimen	Subsidiary Specimen
WIDTH	W	
THICKNESS	$B = 0.5W$	$B = W$
NOTCH THICKNESS	N	
EFFECTIVE NOTCH LENGTH	M	
EFFECTIVE CRACK LENGTH	a	

FIGURE 3.6 – CRACK TIP OPENING DISPLACEMENT SPECIMEN
(REFER TO STANDARD BS 7448 FOR DETAILS)

described in various national standard, and a specimen form is shown diagrammatically in Figure 3.6.

Normally, the CTOD test is performed on the full section thickness of the weld. The test can be applied either to the weld metal using a notch placed at the centerline, or to the HAZ at a preselected location. The most commonly specified location for HAZ testing in steels is the coarse-grained HAZ adjacent to the weld interface. Remember, however, that this idea assumes such location represents the lowest toughness zone. A specific feature of this type of test when applied to HAZ testing is the criticality of accurately placing notch and fatigue cracks, since an error of just 0.25 mm can make a very significant difference to the values obtained. For this reason, HAZ-CTOD data must be supported by metallurgical examination reports on the broken specimens to confirm that the fatigue crack tip has indeed sampled the microstructural zones targeted. A good explanation of such examinations is now provided in various standards [3]. The necessity for accurate notch placement influences the overall approach to such a test program; and, while the testing facility technician must inevitably play a major role in the success of targeting specific microstructural areas, his chance of success is greatly affected by the standard of weld supplied for the test.

Two forms of CTOD testing are relatively common, namely,

- through thickness notch specimen, and
- surface notch specimen.

When testing the through thickness notch specimen, commonly carried out on a single-bevel butt joint weld, it is important that the weld interface be kept reasonably straight so the notch can sample as many areas as possible in the specified microstructure. This often means that additional precautions must be taken during welding, such as controlling wire-to-wall position in submerged arc welding to ensure that the weld interface remains straight. However, some might argue that, even with extra precautions, this method may not produce a test representative of production conditions. When a fully representative sample is demanded, the surface notch approach can be taken; but, this method can be expected to produce a high number of microstructurally invalid test pieces (often in excess of 50 percent), which can become prohibitively expensive. Another approach is described in other literature [1, 2], based on “searching” for the zone of minimum toughness. The methods above, however, are those normally specified.

Another use of the CTOD test is with respect to weldability testing for the qualification of material supply routes. This is now a fairly common requirement for offshore structural fabrication activities, obligating the steel supplier to provide fracture toughness data for all thickness ranges and heat input ranges to be applied during fabrication. Often, by presenting such data, the fabricator can avoid extensive CTOD testing as part of the weld procedure requirements. However, when reviewing such information (supplied, for example, by the steelmaker), ask the following questions:

- Is the data recent and does it reflect current steel chemistry and production routes?

- How independent was the data?
- Were the welds performed by a steelmaker or by a fabricator? Are they representative of fabrication practices?
- Are all results reported? (Beware of data reporting only averages, as this can hide poor minimum values.)

Any assessment the welding engineer makes regarding the overall acceptability of a material must take into account the above factors, as well as purely technical aspects regardless of whether the data is viewed from the specifier's or the fabricator's viewpoint.

Fracture toughness testing of this type remains the exception rather than the rule, and it will not be required in the majority of weld procedure qualifications undertaken. Even so, the welding engineer should make himself aware of the potential for such tests. The ability of the CTOD test to provide information of direct relevance to the designer can sometimes be advantageous to the welding engineer faced with, say, procedure testing, or production-stage Charpy impact test failures. In such situations, resorting to a fracture toughness test can sometimes satisfy the client that the weld is "fit for purpose." Another use of CTOD testing is to justify as-welded fabrication. For instance, by demonstrating good as-welded fracture toughness, the avoidance of expensive postweld heat treatment is sometimes possible (see the section on CTOD, titled Fracture Toughness Justification, in Chapter 6, page 98).

3.5 Test Failures

During procedure testing, it is almost inevitable that the welding engineer will be faced with test failures. Whether these are NDE rejections or mechanical test failures, such failures immediately raise several questions. For example:

- Can the cause of the failure be identified?
- What impact, if any, will the failure have on production programs?
- Can the procedure test be "salvaged" via retests and/or negotiation with the client?
- Is a complete rethink of the proposed welding procedure required?

In a well organized operation, the answer to the second question above should be known in advance, and the amount of time available to the welding engineer prior to a production requirement will obviously affect the way in which a failed procedure test should be approached. For example, if the production need is not immediate, then there may be time to fully assess the reason for the failure and take the required actions in due course. However, if there is little time to spare (or, indeed, the procedure is already late), then the welding engineer can expect little praise for providing an "ideal" solution to the problem in a week or two. A solution in this case is required immediately.

In a time-sensitive situation, the engineer must act quickly to obtain a qualified procedure in the shortest possible time. This may not be the best or most productive weld

procedure, but a better solution can always be adopted later. In this type of situation, it is usually advisable to generate options. For instance, if your instinct tells you that it is possible to convince your client of a procedure's fitness for purpose, then by all means pursue this course of action. In the meantime, however, rerun the procedure with a different weld preparation, consumable, or whatever is suspected to be the source of the initial problem. Delays to production are far more costly than an extra weld procedure test. So, do not waste time waiting for the answer to your first option; it may be negative.

When presented with a test failure, it is important to establish the cause of the failure as soon as possible — or, at least, to rule out all non-causal factors. The cause may be attributable to human error, equipment malfunction, a metallurgical problem, or simply an unsuitable procedure. If the problem is traceable to the equipment used or to the welder (e.g., porosity related to an equipment malfunction or slag inclusions), then it is usually possible to get the procedure accepted on the basis of mechanical properties alone — possibly with the proviso of satisfactory NDE performance on the first production weld. Such occurrences should not be regarded as indicative of poor weld procedures, provided of course that the slag inclusions were not related to some adverse geometrical feature or access problem that made the weld unusually difficult to accomplish.

The engineer's reaction to failed mechanical tests should be governed to some extent by previous experience. If the procedure test was utilizing previously proven technology with respect to the consumables, then the first thing to check is the source and quality of the materials and consumables. At this stage, it is also worth checking whether the same batches, casts, etc., were used in production — especially if serious doubts are arising as to their acceptability.

Finally, it is necessary for the engineer to examine clearly the nature of the failure to eliminate the possibility of simple errors such as incorrectly located specimens, inaccuracy in notch location (impact tests), etc. Even if such a problem is found, the fact remains that a failed result was obtained, and this cannot be ignored. Nevertheless, close examination is required to establish where the problem lies, both technically and contractually; because, if the failure is related to HAZ or base material, then it may be your client's problem (e.g., if the material was free issued or from a contractually specified supplier). This in itself does not solve the technical problem, and it does not absolve the welding engineer from his responsibility to solve the problem; but it may affect who pays the cost of rerunning weld procedures and, more importantly, of delays in production. Contractual responsibilities must, therefore, be borne in mind. A simple decision tree is shown in Figure 3.7 to illustrate the various points noted and actions advised. Note that Figure 3.7 is not intended to provide a fully comprehensive list of questions. The engineer must consider additional questions as necessary.

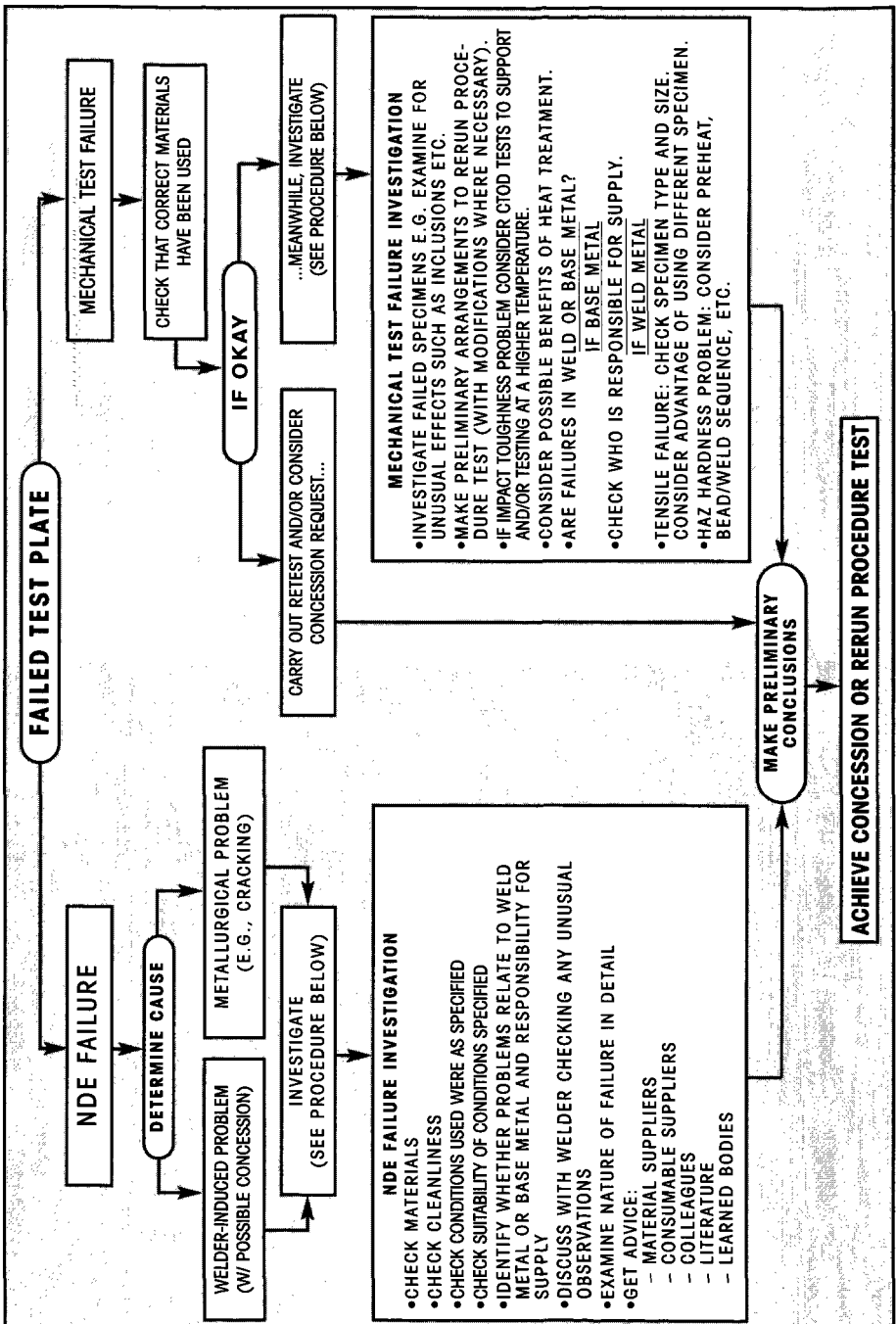


FIGURE 3.7 – FAILED TEST PLATE DECISION TREE

References

- [1] Rodgers, K. J. 1988. Heat-Affected Zones — A Fabricator's Viewpoint. OMAEA 88, Paper 903.
- [2] Private communication of original idea, Tad Boniszewski.
- [3] American Petroleum Institute standard RP-2Z, *Preproduction Qualifications for Steel Plates for Offshore Structures*, 3rd Edition, 1998. Washington D.C.: American Petroleum Institute.

Chapter 4

Production Welding Control

Production welding control is undoubtedly the sharp end of the welding engineer's involvement in any production environment. It cannot be emphasized enough that for manual and semiautomatic applications, and to a lesser extent for machine welding processes, the welder is the most important factor in controlling weld quality. No matter how good the welding procedure appears on paper, or how advanced the consumable or equipment may be, if the welder is not properly instructed, or controlled, the chances of a poor weld resulting from his work increase dramatically. For example, if the welder feels what he is doing is incorrect, or if the fume from the electrode is causing problems, or if the equipment seems awkward or wrong, then the welder will *prove* that *your* procedure led to poor quality.

To help the welder produce good quality welds, there are several factors that must be continually monitored and controlled. These are listed below in the order of importance to a welding engineer, then subsequently examined in detail.

1. Defect analysis
2. Welder training/qualification
3. Supervision
4. Useful aids
5. Consumable control
6. Production tests

4.1 Defect Analysis

This may appear to be a peculiar placing for this topic. However, unless the welding engineer is aware of what the problems actually are, he can make little progress in rectifying them. Many companies benefit from the availability of a defect analysis system. The usual format is one in which percent defect is expressed as defect length divided by weld length. This may be further divided into linear or volumetric defects. The use of weld length as an overall measure is simple to apply but lacks the effect of volume. Consequently it has no absolute meaning, so take care in interpreting such data — especially when a large amount of fillet welding is included in the overall total. In this instance, a problem with a high defect rate on full penetration butt joint welds could be easily masked.