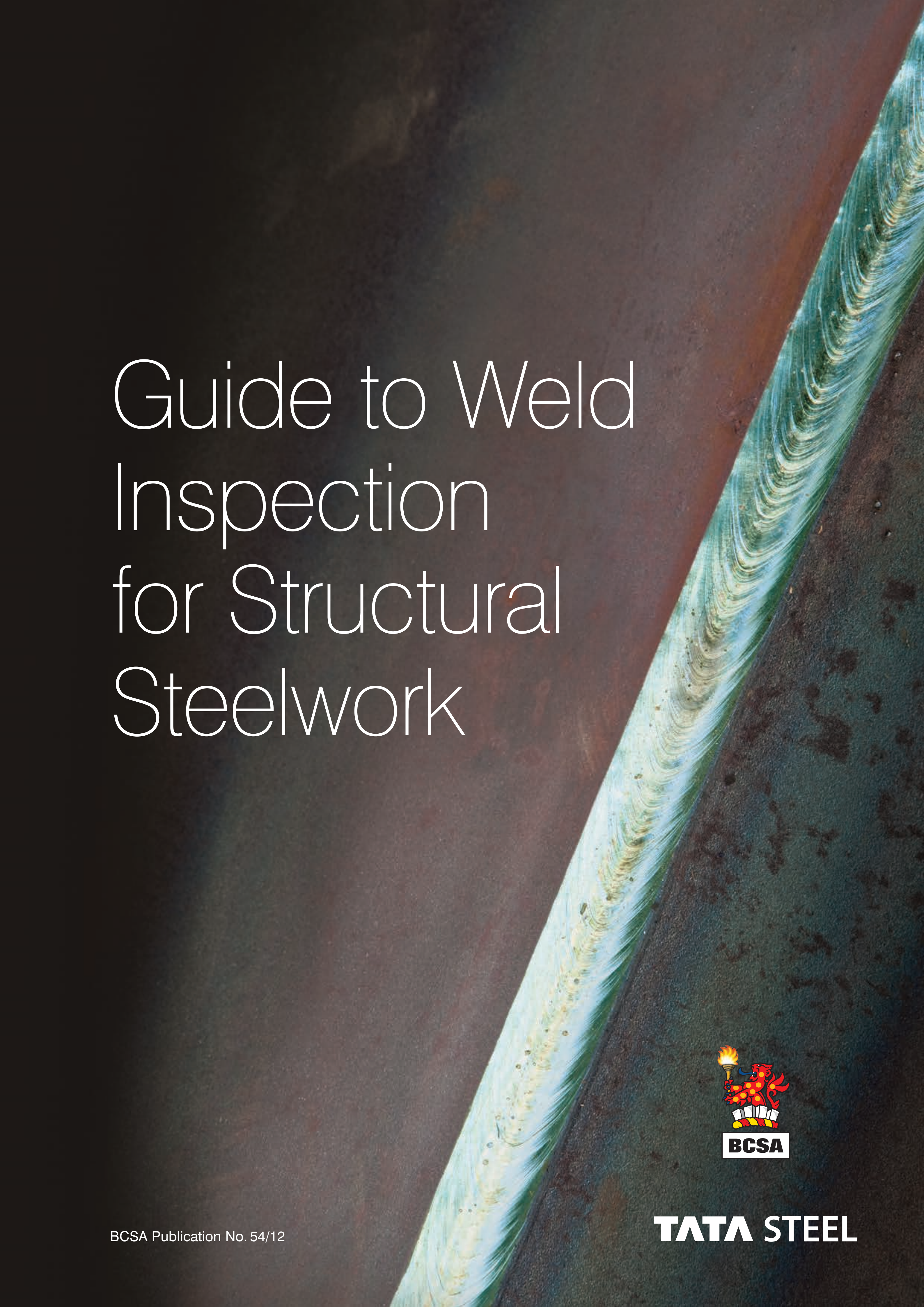

# Guide to Weld Inspection for Structural Steelwork

BCSA

BCSA Publication No. 54/12

TATA STEEL

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## Summary

This publication gives guidance on weld inspection for structural steelwork. It explains how techniques for weld inspection and testing are used to identify and characterise defects that can arise in structural steel components. It also explains the causes of such defects and measures that may be taken to avoid them. The guidance is intended for use by persons undertaking or responsible for weld inspection in fabrication facilities manufacturing structural steel components that are designed for static loading. This technical knowledge is a prerequisite for persons identified as responsible for welding coordination by manufacturers of structural steel components.



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# Contents

# 1 Introduction

*BS EN 1090-2 Execution of steel structures and aluminium structures. Part 2: Technical requirements for the execution of steel structures* requires that a Responsible Welding Coordinator (RWC) be appointed by manufacturers of welded structural steel components in Execution Classes 2, 3 or 4 (EXC2, EXC3 or EXC4).

The BCSA's *Guide to the CE Marking of Structural Steelwork* explains the guidance given to Notified Bodies certifying factory production control (FPC) systems for manufacturing welded structural steel components which states that:

> With respect to the processes being used, the Execution Class for the products being produced, the constituent products being welded and the welding consumables being used, the assessment of the RWC's competence shall include the following checks with respect to the RWC's ability to coordinate the processes etc within the FPC System:
>
> - During a technical discussion, check the knowledge of the welding coordinator(s) about the relevant standards, regulations and specifications to be observed.
> - Check the ability of the welding coordinator(s) to detect and assess defects, to instruct repairs and to know how to avoid defects.

This publication has been prepared to provide guidance on how to detect and assess defects and how to avoid defects in welded structural steel components that are designed for static loading.

# 2 Scope

This guide is complementary to the BCSA's *National Structural Steelwork Specification for Building Construction 5th Edition CE Marking Version* (NSSS) which states that "it can be used for all types of building construction designed for static loading. It is based on execution of structural steelwork in Execution Class 2 according to BS EN 1090-2. It is not intended to be used for steelwork in dynamically or seismically loaded structures or if fatigue is a factor unless appropriate amendments are made".

The guide is generally focused on the types of defects that are likely to arise in steels in strength grades up to S355 that are welded using the following welding processes:

111: Manual metal-arc welding (metal-arc welding with covered electrode); or

135: Metal active gas welding; MAG-welding.

This guidance is also complementary to BCSA's *Typical Welding Procedures for Structural Steelwork*.

# 3 Overview

## 3.1 NDT/NDE Methods

BS EN 1090-2 states:

> Non-destructive testing (NDT) methods shall be selected in accordance with EN 12062 by personnel qualified according to Level 3 as defined in EN 473. Generally ultrasonic testing or radiographic testing applies to butt welds and penetrant testing or magnetic particle inspection applies to fillet welds.

BS EN 12062 *Non-destructive examination of welds — General rules for metallic materials* refers to the following non-destructive examination (NDE) methods:

ET Eddy current testing

MT Magnetic particle testing (often referred to as MPI)

PT Penetrant testing (often referred to as dye penetrant testing)

RT Radiographic testing (often referred to as X-ray testing)

UT Ultrasonic testing

VT Visual testing (often termed visual inspection)

BS EN 1090-2 refers to “visual inspection” for VT and groups the other methods of NDE listed above as “supplementary NDT”.

BS EN 12062 provides guidance on which of the six methods listed are more effective in different situations, and states:

Before selecting testing methods and levels, the following items should be considered:

— welding processes;

— parent metal, welding consumable and treatment;

— joint type and geometry;

— component configuration (accessibility, surface condition, ...);

— quality levels;

— imperfection type and orientation expected.

NSSS (following BS EN 1090-2) specifies the use of the following methods:

- MT rather than PT for identifying and characterising surface breaking discontinuities;
- UT rather than RT for identifying and characterising sub-surface discontinuities (also termed volumetric discontinuities);
- ET for post-galvanizing inspection to determine whether liquid metal assisted cracking has occurred.

The avoidance of RT has advantages in terms of safe practice as risk limitation is difficult for RT.

MT is a practical method for structural steels as they have the necessary magnetic properties.

## 3.2 Imperfections and Defects

All welds exhibit some imperfections in terms of either shape or metallic discontinuities. The purpose of testing is to be able to characterise such imperfections in order to determine whether they are defects that require remedial action. The remedial action may necessitate repair of the weld or adjustment of the welding process parameters or both. This occurs when the imperfections exceed the acceptance criteria specified in the standard. BS EN ISO 6520-1 provides the following definitions:

- Imperfection: any deviation from the ideal weld.
- Defect: an unacceptable imperfection.

BS EN 12062 explains how “indications” (arising from the testing method being used to characterise imperfections) are dealt with depends on the “testing level” being employed, which is defined as follows:

> The testing level is the degree of thoroughness and selection of parameter settings with which testing method is applied. Different levels correspond to different sensitivities and/or probabilities of detection.

In terms of NDT, BS EN 12062 explains that some indications may be so slight as to be below the level that can be reliably characterised. Above this evaluation level, some indications may be too small to be worth recording. Above this recording level, decisions are needed as to whether the indication is an imperfection or a defect.

Clearly the ability of a method like UT to evaluate an indication depends on the capability of the instrumentation, the settings used and the skill of the operator. In terms of the technique used for UT, NSSS states:

> If ultrasonic testing is required, it shall be made in accordance with BS EN 1714 using reference level to Method 1, evaluation reference level -14dB (20% DAC) and testing level B unless determined otherwise by the Steelwork Contractor’s responsible welding coordinator.

BS EN ISO 5817 *Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections* provides a selection of fusion weld imperfections. Importantly in its introduction the standard states:

> The purpose of this International Standard is to define dimensions of typical imperfections which might be expected in normal fabrication. It may be used within a quality system for the production of factory-welded joints. It provides three sets of dimensional values from which a selection can be made for a particular application. The quality level necessary in each case should be defined by the application standard or the responsible designer in conjunction with the manufacturer, user and/or other parties concerned. The level shall be prescribed before the start of production, preferably at the enquiry or order stage. For special purposes, additional details may be prescribed.

> The quality levels given in this International Standard provide basic reference data and are not specifically related to any particular application. They refer to the types of welded joint in a fabricated structure and not to the complete product or component itself. It is possible, therefore, that different quality levels be applied to individual welded joints in the same product or component.
>
> It would normally be expected that for a particular welded joint the dimensional limits for imperfections could all be covered by specifying one quality level. In some cases, it may be necessary to specify different quality levels for different imperfections in the same welded joint.
>
> The choice of quality level for any application should take account of design considerations, subsequent processing (e.g. surfacing), mode of stressing (e.g. static, dynamic), service conditions (e.g. temperature, environment) and consequences of failure. Economic factors are also important and should include not only the cost of welding but also of inspection, test and repair.

As explained below, BS EN 1090-2 and the NSSS specify which types of imperfection are important for structural welds and the relevant quality levels to be used as acceptance criteria.

## 3.3 Destructive Testing

Clearly it is not possible to use destructive testing on production weldments, but such methods are used in qualification testing of welders and welding procedures. Some weld imperfections specified in BS EN ISO 5817 are difficult to characterise using NDT, and destructive tests are needed. The additional test methods possible in destructive testing are tensile tests, hardness tests, impact tests, bend tests, macroscopic and microscopic examination.

Also, some weldment configurations limit the ability of NDT methods to access the welded joints, and some welded joints (e.g. unbacked butt welds) limit the ability to obtain reliable readings. In such cases it may be necessary to weld a test piece under the general conditions of production welding and then to section the test piece for destructive testing. This qualification method is specified in BS EN ISO 15613 *Specification and qualification of welding procedures for metallic materials — Qualification based on pre-production welding test.*

## 3.4 Acceptance Criteria

The acceptance criteria enable a weld to be "sentenced" in that they provide the basis for evaluation and judgement of observed NDE evidence against specified requirements. The quality of the observed NDE evidence is dependent on the technique(s) being used, as explained in BS EN 12062 which provides:

> The correlation between the quality levels of EN 25817 (*now EN ISO 5817)* or EN 30042 and the testing techniques, testing levels and acceptance levels of non-destructive testing standards.

BS EN 1090-2 specifies the acceptance criteria on what BS EN 12062 terms the "quality assurance acceptance level". These criteria are used for monitoring the ongoing quality of production welding using routine testing, which is explained in NSSS as follows:

> Provided that it has been established that WPSs in use can produce conforming quality when implemented in production according to 5.5.2, ongoing control of welding quality shall be maintained by routine testing.
>
> Routine testing includes 100% visual inspection to 5.5.3 and a supplementary programme of non-destructive testing (NDT) which shall be undertaken by the Steelwork Contractor to ensure that the welding processes and welders / welding operators are producing work of a quality that is consistent with Execution Class 2.
>
> The benchmark for the quality of work required for Execution Class 2 is generally quality level C to BS EN ISO 5817 with the certain *(defined)* exceptions.

BS EN 12062 also defines a "fitness for purpose (FFP) acceptance level". With respect to FFP criteria, BS EN 1090-2 states:

> In case of nonconformities with the above *(routine quality assurance)* criteria, each case should be judged individually. Such evaluation should be based on the function of the component and the characteristics of the imperfections (type, size, location) in order to decide whether the weld is either acceptable or shall be repaired.

NSSS tabulates the FFP acceptance criteria relevant to welds in structural steel components that are designed for static loading. These are reproduced in section 6 of this guide. They are based on a study undertaken for the BCSA by the Welding Institute (TWI). TWI has also determined suitable FFP criteria for welds subject to fatigue loading, and those are tabulated in ISO 10721-2 *Steel structures — Part 2: Fabrication and erection* and form the basis of the recommendations in PD 6705-2 *Structural use of steel and aluminium. Part 2: Recommendations for the execution of steel bridges to BS EN 1090-2.*

Thus, when a weld is sentenced by evaluating the NDE evidence against the acceptance criteria, this may indicate that:

- the process is not producing welds that meet the required quality assurance acceptance level, and the welding process parameters require adjustment; or
- the individual weld itself does not meet the fitness for purpose (FFP) acceptance level, and that weld needs to be repaired; or
- both.

## 3.5 Inspection and Test Plan

The important factor to be remembered in undertaking routine and other inspection and testing of welds is to be clear on what action to take if defects are found. Two principal actions would follow:

- Does the weld require remedial correction, and if so how?
- Why did the non-conformity occur, and how can recurrence be prevented?

The first is in essence a FFP issue. The second is an issue of process control quality assurance.

There is also what may be termed a "hierarchy" of inspection/testing. At the first level, welders are required to visually self-inspect their own work. NSSS provides practical guidelines for visual inspection of welds. In terms of visual inspection and corrective action, it states:

> A suitably qualified person for visual inspection of welds may be a welding inspector or a welder who can provide evidence of having been trained and assessed for competence in visual inspection of the relevant types of welds during and after welding. Additional visual inspection as audit checking shall be carried out by an NDT technician qualified to the requirements of BS EN 473.
>
> *Note: The initial 100% visual inspection is often undertaken by the welder and is aimed at verifying that the weld has been completed satisfactorily to allow the welder to progress. Defects visible at this stage can often be repaired immediately by the welder (see Table C.1 in Annex C). The need for additional visual inspection is often the prelude to deciding whether to investigate further using supplementary NDT (see 5.5.5).*
>
> Corrective action on minor defects capable of immediate rectification may be taken under the authority of the visual inspector. More significant defects shall be reported using a non-conformance procedure, and corrective action undertaken before further NDT including additional visual inspection. A record shall be kept that visual inspection has been carried out and any non-conformities identified.

These clauses illustrate how visual inspection by the welder (or the shop inspector or supervisor) may lead to immediate rectification (e.g. weld geometry or profile discontinuities such as at stop-start positions). More problematic indications would be referred to the second level as nonconformities. For instance, crack indications would require further investigation – initially additional visual inspection and then MT and possibly UT.

Clearly, visual inspection cannot identify sub-surface discontinuities. Hence, it is important to focus UT on those joints where such discontinuities are more likely and more critical. Both BS EN 1090-2 and NSSS specify the joints where routine supplementary NDT (MT and UT) is to be employed. Generally these are on butt welds and larger fillet welds in thicker materials as shown in Table A below taken from Annex B of the NSSS.

It is noted in the table that all welds based on the same WPS may be treated as a "single continuing inspection lot". This will be the case during routine inspection so that the RWC's percentage selection of welds to be inspected by MT or UT does not need to be based on a project-by-project basis. The selection will typically be based on the weekly programme of work being undertaken in the welding workshop. Knowing the mix of work and using the table above, the welds that need to be subjected to MT and/or UT can be identified in advance, and the components routed accordingly. If there are many such components, then it is not difficult to test, say, 1 in 10. For smaller numbers it may not be possible to be exact, and a greater percentage may need to be tested. The important factor is to ensure that the percentage tested is selected in a way that gives sound evidence about the quality of welding work being undertaken. Maintaining product quality by testing is far more efficient and far less disruptive than late realisation that repair and/or product recall is needed.

Some specifiers may require project-specific testing. This may be counted within the extent of routine testing, as appropriate.

**TABLE A – EXTENT OF ROUTINE SUPPLEMENTARY NDT**

| **Weld Type (1)** | **Extent (2)** |
|---|---|
| Full or partial penetration butt welds (other than welds to stiffeners or longitudinal welds) | 10% magnetic particle testing (MT) |
| Full or partial penetration butt welds in material being joined with a maximum nominal thickness >10mm | 10% ultrasonic testing (UT) |
| Fillet welds with nominal throat thickness > 12mm, nominal leg length > 17mm or in material being joined with a maximum nominal thickness > 20mm | 10% MT and 5% UT (3) |

(1) Provided that site welding is undertaken under the control of a suitably competent welding coordinator on site and appointed by the RWC, these requirements generally make no distinction between shop and site welds. However, the extent of testing for the weld types above shall be 100% for site welds on a new project until the RWC is satisfied that suitable quality levels can be maintained.

*Note: This applies the principles in 5.5.2 for initial type testing to the supplementary NDT for welds on the site of a new project.*

(2) The percentages are subject to a minimum length of 900mm in any inspection lot and apply to the cumulative amount of weld length in joints welded according to the same WPS treated as a single continuing inspection lot. An inspection lot is a group of welds expected to show a uniform quality. See also 5.5.1 for workshops where no supplementary NDT is required by this Table.

(3) Ultrasonic testing of fillet welds shall be carried out using 0° probes to determine the absence of defects in the parent material.

# 4 Visual Inspection of Welds

## 4.1 Introduction

Whilst MT and UT are often undertaken by external specialist inspectors, visual inspection (VT) is always undertaken, at least in part, by the manufacturer's own personnel – hence the inclusion of this more detailed guidance on visual inspection in this guide. In practice, although visual inspection is just one of the NDE disciplines, for many structural steelwork applications it may be the only form of NDE required.

For more demanding service conditions, visual inspection is usually followed by surface crack detection and for butt and larger fillet welds some form of volumetric inspection. For structural steelwork the other techniques typically applied are MT and UT respectively.

Application standards usually specify the acceptance criteria for weld inspection and may be very specific about the particular techniques to be used for surface crack detection and volumetric inspection. However, they do not usually give any guidance about basic requirements for visual inspection.

Guidance and basic requirements for visual inspection is given in BS EN ISO 17637 *Non-destructive testing of welds — Visual testing of fusion-welded joints (which superseded BS EN 970 in 2011).*

BS EN ISO 17637 outlines the following information:

- requirements for welding inspection personnel;
- recommendations about conditions suitable for visual examination;
- the use of gauges/inspection aids that may be needed/helpful for inspection;
- guidance about when inspection may be required during the stages of fabrication;
- guidance about information that may need to be included in the inspection records.

A summary of each of these topics follows.

## 4.2 Welding Inspection Personnel

Before starting work on a particular contract, BS EN ISO 17637 states that welding inspectors should:

- be familiar with relevant standards, rules and specifications for the fabrication work that is to be undertaken;
- standards may be National or Client;
- be informed about the welding procedure(s) to be used;
- have good vision – in accordance with EN 473 and should be checked every 12 months.

It has become industry practice for inspectors to have practical experience of welding inspection together with a recognised qualification in Welding Inspection such as PCN or CSWIP.

## 4.3 Conditions for Visual Inspection

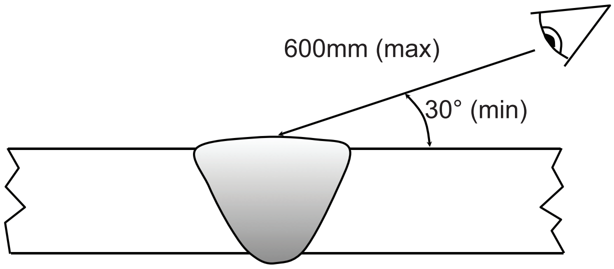
### 4.3.1 Illumination

BS EN ISO 17637 states that the minimum illumination shall be 350 lux but recommends a minimum of 500 lux (normal shop or office lighting).

### 4.3.2 Access

Access to the surface, for direct inspection, should enable the eye:

- to be within 600mm of the surface being inspected;
- to be in a position to give a viewing angle of not less than 30°.




### 4.3.3 Aids to visual inspection

Where access is restricted for direct visual inspection, the use of a mirrored borescope, or a fibre optic viewing system, are options that may be used – usually by agreement between the contracting parties.

It may also be necessary to provide auxiliary lighting (such as torch) to give suitable contrast and relief effect between surface imperfections and the background.

Other items of equipment that may be appropriate to facilitate visual examination are:

- welding gauges – for checking bevel angles and weld profile, fillet sizing, measuring undercut depth;
- dedicated weld-gap gauges and linear misalignment (high-low) gauges;
- straight edges and measuring tapes;
- magnifying lens – if magnification lens used to aid visual examination it should be x2 to x5 magnification.

BS EN ISO 17637 illustrates a range of welding gauges together with details of what they can be used for and the precision of the measurements that can be made.

## 4.4 Visual Inspection Duties

### 4.4.1 Stages when inspection may be required

Visual inspection of the finished weld is a minimum requirement.

For fabricated items that must have high "integrity", such as large structures, inspection activity will usually be required throughout the fabrication process, namely:

- before welding;
- during welding; and
- after welding.

Inspection activities at each of these stages of fabrication can be considered to be the duties of the welding inspector and typical inspection checks that may be required are described below.

### 4.4.2 Typical duties of a welding inspector

The relevant standards, rules and specifications that a welding inspector should be familiar with at the start of a new contract are all the documents required for reference during the fabrication sequence in order to make judgements about particular details.

Typical documents that may need to be referred to are:

- the application standard (for visual acceptance criteria - see note below);
- quality plans or inspection check lists (for the type and extent of inspection);
- drawings (for assembly/fit-up details and dimensional requirements);
- quality procedures (such as those for document control, material handling, electrode storage and issue, WPSs etc).

*Notes:*

*Although most of the requirements for the fabricated item should be specified by standards, project specification and/or company quality procedures, some features are not easy to define precisely and the requirement may be given as "to good workmanship standard".*

*Examples of requirements that are difficult to define precisely are some shape tolerances, distortion, surface damage or the amount of weld spatter.*

*"Good workmanship" is the standard that a competent worker should be able to achieve without difficulty when using the correct equipment in a particular working environment.*

*In practice the application of the fabricated item will be the main factor that influences what is judged to be good workmanship as well as the standard that a particular manufacturer has become used to to satisfy particular clients.*

*"Reference" samples are sometimes needed to give guidance about the acceptance standard for details such as weld surface finish and toe blend, weld root profile and finish required for welds that need to be dressed by grinding or finishing.*

A welding inspector should also ensure that any inspection aids that will be needed are in good condition and calibrated as appropriate and/or as specified by quality procedures.

Safety consciousness is a duty of all employees and a welding inspector should be aware of all safety regulations for the workplace, and ensure that safety equipment that will be needed is available and in suitable condition.

### 4.4.3 General duties

In discharging the duties before, during and after welding described in the following three tables, the weld inspector would be assisted by the shop supervisor and others involved in welding coordination.

**DUTIES BEFORE WELDING**

| Check | Action |
|---|---|
| **Material** | is in accordance with drawing and/or WPS is identified and can be traced to a test certificate is in suitable condition (free from damage or contamination) |
| **WPSs or Work Instructions** | are based on suitable WPQRs and are available to welders (and inspectors) |
| **Welding Equipment** | is in suitable condition and validated as appropriate |
| **Weld Preparations** | are in accordance with WPS (and/or drawings) |
| **Welder Qualifications** | identification of welders qualified for each WPS to be used all welder qualification certificates are valid ("in-date") |
| **Welding Consumables** | those to be used are as specified by the WPSs are being stored/controlled as specified by the quality procedure |
| **Joint Fit-ups** | are in accordance with WPS and/or drawings tack welds are to good workmanship standard and to WPS |
| **Weld Faces** | are free from defects, contamination or damage |
| **Preheat (if required)** | minimum temperature before and during welding is in accordance with WPS |

**DUTIES DURING WELDING**

| Check | Action |
|---|---|
| **Site/field Welding** | ensure weather conditions are suitable / comply with standard (to ensure conditions will not affect welding) |
| **Welding Process** | is in accordance with WPS |
| **Preheat (if required)** | minimum temperature is being maintained in accordance with WPS |
| **Inter-pass Temperature** | maximum temperature is in accordance with WPS |
| **Welding Consumables** | are correct to WPS<br>are being controlled as procedure |
| **Welding Parameters** | current, volts, travel speed, are in accordance with WPS |
| **Root Run** | is visually acceptable (before filling the joint) (for single sided welds) |
| **Gouging or Grinding** | is by an approved method<br>is to a good workmanship standard |
| **Inter-run Cleaning** | is to good workmanship standard |
| **Welder** | is on the approval register/qualified for the WPS being used |

**DUTIES AFTER WELDING**

| Check | Action |
|---|---|
| **Weld / Welder Identification (if required)** | each weld is marked with the welder's identification; each weld is identified in accordance with drawing / weld map |
| **Weld Appearance** | ensure welds are suitable for all NDT techniques being used (profile, cleanness etc) visually inspect welds and evaluate / "sentence" in accordance with specified criteria |
| **Dimensional Survey** | check dimensions are in accordance with drawing / standard |
| **Drawings** | ensure any modifications are included on "as-built" drawings |
| **NDT** | ensure all NDT is complete and reports are available for records |
| **Repairs** | monitor in accordance with the procedure |
| **PWHT (if required)** | monitor post-weld heat treatment for compliance with procedure (check chart record) |
| **Documentation Records** | ensure all reports / records are completed and collated as required |

### 4.4.4 Routine duties

Annex D of the NSSS (reproduced below) provides specific guidelines with respect to the duties undertaken during routine VT by the welder.

**Prior to welding or between weld passes**

(i) Check that the weld preparation is correct in accordance with the welding work instruction. Items to be checked include preparation angles, root gap, root face condition, depth of preparation for part penetration welds, minimal gap for fillet welds.

(ii) Check that the area to be welded is not contaminated with grease, oil, dirt, paint or moisture.

(iii) Check that any tack welds have been removed or are suitable for welding over.

(iv) For multi-pass welds, check the suitability of the surface of previously deposited weld metal. In addition to checking any re-preparation to (i) and cleanliness to (ii), the area to be welded shall be de-slagged, free of weld spatter and be of a suitable profile for deposition of the subsequent pass.

(v) Check that the relative position of parts to be joined is in accordance with the Fabrication Drawings and that the joint fit-up is satisfactory.

(vi) Check the shape and depth of any back gouging to ensure the complete removal of the second side back to sound metal. Also check whether supplementary NDT is needed at this stage before proceeding.

**After deposition of each weld pass or at final completion**

(i) Check the weld size. Visual estimation may be used to assess acceptability, but, if in doubt, check by measurement. Confirm by measurement periodically anyhow.

(ii) Check that welds are complete. Items to be checked include whether the weld extends fully to the end of the preparation or run-on/run-off plates if used for butt welds, and that return welds are completed.

(iii) Check that any craters have been filled and that no crater cracks are evident visually.

(iv) Check for undercut, and measure for evaluation if identified.

(v) Check that the weld beads are of even appearance and that fillets present a mitre or slightly convex profile and butt welds are not under-flush with incomplete grooves. Measure any concave profiles to ensure that the specified throat thickness has not been compromised.

(vi) Check for absence of any cracking or significant porosity.

(vii) Check for absence of overlapping.

(viii) Check for absence of any mechanical damage from tool marks (e.g. chisels, hammers).

**Corrective action**

Corrective action on minor defects capable of immediate rectification may be taken under the authority of the visual inspector. More significant defects shall be reported using a non-conformance procedure, and corrective action undertaken before further NDT including additional visual inspection. A record shall be kept that visual inspection has been carried out and any non-conformities identified.

### 4.4.5 Examination records

The requirement for examination records/inspection reports will vary according to contract and type of fabrication and there is frequently no requirement for a formal record.

If an inspection record is required it may be necessary to show that items have been checked at the specified stages and that they have satisfied the acceptance criteria.

The form of this record will vary – possibly a signature against an activity on an inspection checklist or on a quality plan, or it may be an individual inspection report for each item.

For individual inspection reports typical details are:

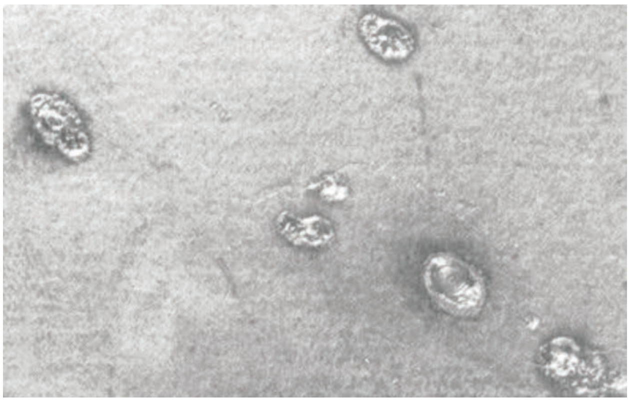
- name of manufacturer;
- identification of item examined;
- material type and thickness;
- type of joint;
- welding process;
- acceptance standard/acceptance criteria;
- locations and types of all imperfections not acceptable (when specified, it may be necessary to include an accurate sketch or photo);
- name of examiner/inspector and date of examination.

# 5 Weld Defects and Causes

## 5.1 Weld Technique

### 5.1.1 Stray arc

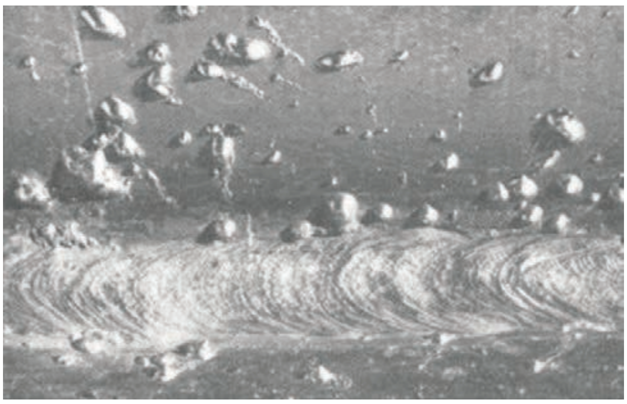
**Description:** Local damage to the surface of the parent metal adjacent to the weld, resulting from arcing or striking the arc outside the weld groove. The result is in the form of random areas of fused metal where the electrode, the holder, or earth return clamp has accidentally touched the work. Arc strikes can produce localised hardened zones that may contain cracks. These can lead to serious cracking in service and should be removed; preferably by grinding rather than weld repair.



| Causes | Prevention |
|---|---|
| Poor access to the work | Improve access (modify assembly sequence) |
| Missing insulation on electrodes holder or torch | Carry out regular inspection of equipment |
| Loose earth return clamp | Ensure earth return clamp is securely fastened |

### 5.1.2 Spatter

**Description:** Globules of weld or filler metal expelled during welding and adhering to the surface of the parent material or solidified weld metal. Spatter in itself is a aesthetic imperfection and does not affect the integrity of the weld. However, as it is usually caused by an excessive welding current, it is a sign that the welding conditions are not ideal.



| Causes | Prevention |
|---|---|
| Arc current too high | Reduce arc current |
| Magnetic arc blow | Reduce arc length or switch to AC |
| Incorrect settings for MAG process | Modify electrical settings (current / voltage) |
| Wrong selection of shielding gases (e.g.100% $CO_2$ in spray transfer) | Increase argon content if possible |

## 5.2 Weld Geometry, Shape and Dimensions

### 5.2.1 Weld geometry

Some of the most common defects occurring in production welds are lapses in ensuring that welds are:

- correctly located;
- not missed;
- the correct type (e.g. partial penetration as opposed to fillet); and
- the correct length (e.g. when intermittent welds are specified).

### 5.2.2 Weld profile

Another set of common defects occurring in production welds are errors in weld profile, such as:

- incorrect throat thickness;
- incorrect leg length; or
- poor toe angle (especially critical for welds subject to fatigue loading).

In terms of profile, both throat thickness and leg length are important, however welds are specified in terms of only one of these parameters – traditionally leg length but throat thickness is preferred in current standards. It is important to eliminate confusion between which is being specified by ensuring only one practice is being used in instructions issued to welders and inspectors. This should nowadays be in terms of throat thickness, but a requirement for 6mm throat would imply a leg length of around 9mm so a misinterpretation would result in an under-size weld that is clearly more dangerous than a weld that is incorrectly over-sized.

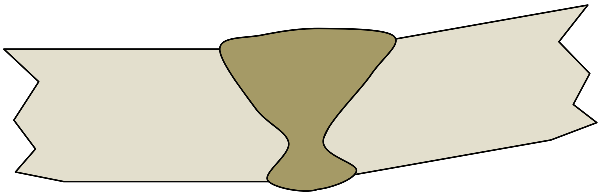
### 5.2.3 Linear misalignment

**Description:** Misalignment between two welded pieces such that while the surface planes are parallel, they are not in the required same plane.

| Causes | Prevention |
|---|---|
| Inaccuracies in assembly procedures or distortion from other welds | Adequate checking of alignment prior to welding coupled with the use of clamps and wedges etc. |
| Excessive out of flatness in hot rolled plates or sections | Check accuracy of rolled section prior to welding |

### 5.2.4 Angular misalignment

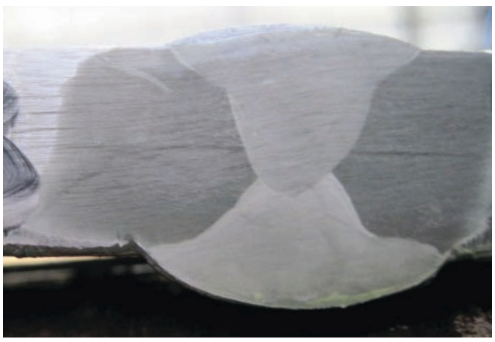
**Description:** Misalignment between two welded pieces such that their surface planes are not parallel or at the intended angle.



Causes and prevention are the same as those for linear misalignment.

### 5.2.5 Excess weld metal

**Description:** Excess weld metal is the extra metal that produces excessive convexity in fillet welds and a weld thickness greater than the parent metal plate in butt welds. This feature of a weld is regarded as an imperfection only when the height of the excess weld metal is greater than a specified limit.

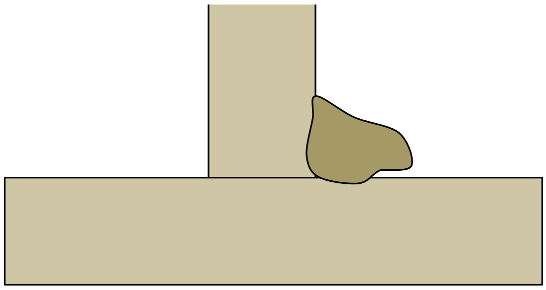


| Causes | Prevention |
|---|---|
| Excess arc energy (MAG, SAW) | Reduce heat input |
| Shallow edge preparation | Deepen the edge preparation |
| Faulty electrode manipulation or build-up sequence | Improve welder skill |
| Incorrect electrode size (too large) | Reduce electrode size |
| Too slow a travel speed | Ensure correct travel speed is used |
| Incorrect electrode angle | Ensure correct angle is used |

This imperfection can become a problem due to the angle of the weld toe. Sharp angles lead to increased stress concentrations and may lead to fatigue cracking in certain service conditions.

### 5.2.6 Overlap

**Description:** An imperfection at the toe of a weld caused by metal flowing on to the surface of the parent metal without fusing to it.

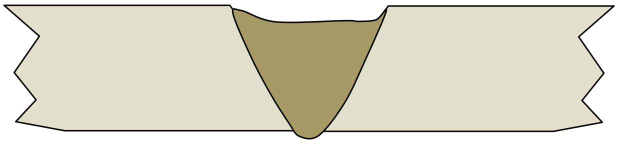


| Causes | Prevention |
|---|---|
| Poor electrode manipulation | Improve welder skill |
| High heat input with too slow a travel speed | Reduce heat input or limit size of deposited weld by using a multi-run technique |
| Incorrect positioning of weld | Change to flat (PA) position |
| Incorrect electrode type (MMA) | Change electrode for one with a faster freezing slag that is less fluid |

For fillet welds, overlap is usually associated with undercut on the top leg where if the weld pool is too fluid it will flow away to produce undercut at the top toe and overlap at the bottom.

### 5.2.7 Incompletely filled groove

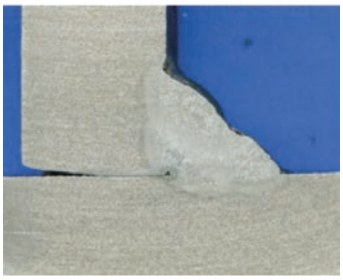
**Description:** A continuous or intermittent channel in the surface of a weld due to insufficient deposition of weld filler metal, thereby reducing load bearing capacity of the weld.



| Causes | Prevention |
|---|---|
| Insufficient weld metal | Increase the number of weld runs |
| Irregular weld bead surface | Improve welder skill |

### 5.2.8 Undercut

**Description:** An irregular groove at the toe of a run in the parent metal or in previously deposited weld metal due to welding. It is characterised by its depth, length and sharpness.



Undercut falls into three distinct categories:

- continuous;
- intermittent; or
- inter-run.

| Causes | Prevention |
|---|---|
| Melting of top edge due to high welding current or high travel speed | Reduce welding current and / or slow travel speed down |
| Excessive / incorrect weaving | Reduce weave width or switch to multi-run technique |
| Incorrect electrode angle | Direct arc to spread heat evenly between the members being joined |
| Incorrect shielding gas selection (MAG) | Ensure correct gas mixture for material type and thickness (MAG) |

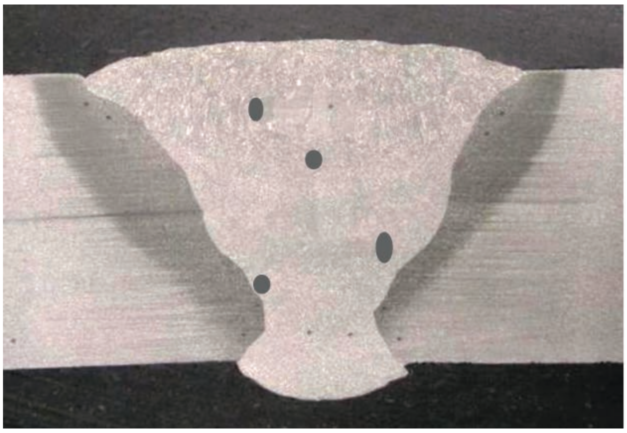
It should be noted that care must be taken during weld repairs of undercut to control the heat input. If the bead of a repair weld is too small, the cooling rate following welding will be excessive and the parent metal may have an increased hardness and the weld may be susceptible to hydrogen cracking.

## 5.3 Cavities

### 5.3.1 Gas pores

**Description:** A gas cavity of essentially spherical shape trapped within the weld metal. This gas cavity can be present in various forms:

- Isolated;
- uniformly distributed porosity;
- clustered (localised) porosity;
- linear porosity;
- elongated cavity; or
- surface pore.



| Causes | Prevention |
|---|---|
| Damp fluxes / corroded electrode (MMA) | Use dry electrodes in good condition |
| Grease / hydrocarbon, water contamination of prepared surface | Clean prepared surface |
| Air entrapment in gas shield (MAG/MIG/TIG) | Check hose connections |
| Incorrect / insufficient deoxidant in electrode, filler or parent material | Use electrode with sufficient deoxidation activity |
| Too high an arc voltage or arc length | Reduce voltage and / or arc length |
| Gas evolution from primers / surface treatments | Identify risk of reaction before surface is treated. Remove primer / treatment local to the weld area |
| Too high a shielding gas flow rate resulting in arc / gas turbulence (MAG/MIG/TIG) | Optimise gas flow rate |

### 5.3.2 Wormholes

**Description:** Elongated or tubular cavities formed by entrapped gas during the solidification of the weld metal; they can occur singly or in groups. They are typically caused by the entrapment of gas between the solidifying metal crystals producing characteristic elongated pores of circular cross-section some of which may break the surface of the weld.

| Causes | Prevention |
|---|---|
| Grossly contaminated plate surface | Review pre-weld cleaning procedures |
| Laminated work surface | Replace parent material |
| Crevices in work surface due to joint geometry | Redesign joints to eliminate crevices |

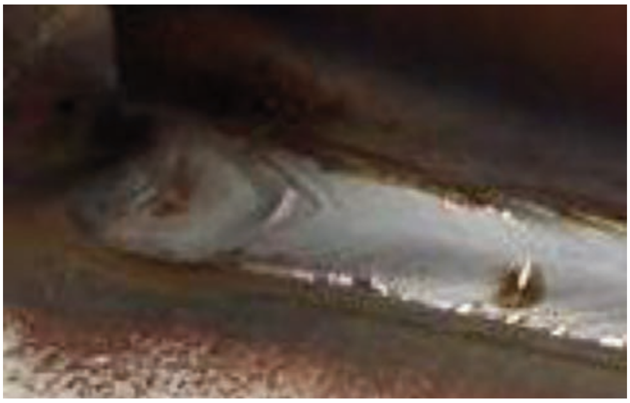
### 5.3.3 Surface porosity

**Description:** A gas pore that breaks the surface of the weld

| Causes | Prevention |
|---|---|
| Damp or contaminated plate surface or damp electrode | Clean surface to remove contaminants and dry electrodes |
| Loss of shielding gas due to long arc lengths or draughty conditions | Screen against draughts and reduce arc length |
| Too high a shielding gas flow rate resulting in arc / gas turbulence (MAG/MIG/TIG) | Optimise gas flow rate |

### 5.3.4 Crater pipe

**Description:** A shrinkage cavity at the end of a weld run. The main cause is shrinkage during solidification.



| Causes | Prevention |
|---|---|
| Rapid termination of the arc preventing adequate crater fill | Improve welder technique for crater fill or use run-off plate |
| Inoperative crater filler (Slope out) when TIG welding | Use correct crater filling techniques |

## 5.4 Cracks

### 5.4.1 Introduction

**Description:** An imperfection produced by a local rupture in the solid state, which may arise from the effect of cooling or stresses. Cracks are more significant than other types of imperfection, as their geometry produces a large stress concentration at the crack tip, making them more likely to cause fracture.

Types of cracks:

- longitudinal cracks;
- transverse cracks;
- radiating cracks (cracks radiating from a common point);
- crater cracks; or
- branching cracks (a group of connected cracks originating from a common crack).

With the exception of crater cracks, that can only be found in the weld metal, all of the other types of crack listed can be situated:

- in the weld metal;
- in the HAZ; or
- in the parent metal.

Depending on their nature cracks can be:

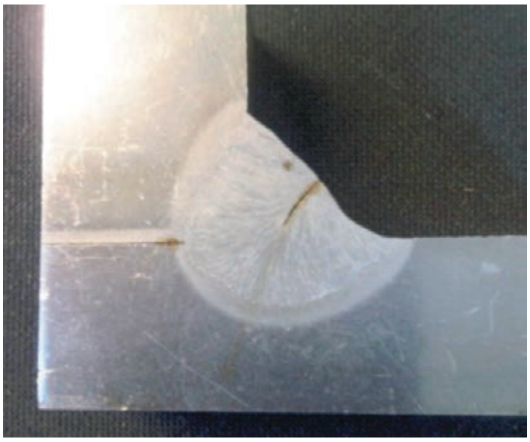
- hot cracks (i.e. solidification cracks);
- precipitation induced cracks (i.e. reheat cracks);
- cold cracks (i.e. hydrogen induced cracks);
- lamellar tears.

### 5.4.2 Solidification cracks

Depending on their location and mode of occurrence, hot cracks can be either solidification cracks or those caused by liquation. In structural steelwork liquation cracks are not normally an issue and so are not discussed. Hot cracks in structural steelwork are typically solidification type cracks, occurring in the weld metal (usually along the centreline of the weld) as a result of the solidification process.

Solidification cracking can be wide and open to the surface, like shrinkage voids, or sub-surface and possibly narrow. It is most likely to occur in compositions, which result in a wide freezing temperature range. In steels this is commonly created by a higher than normal content of carbon and impurity elements such as sulfur and phosphorus. These elements segregate during solidification, so that intergranular liquid films remain after the bulk of the weld has solidified. The thermal shrinkage of the cooling weld bead can cause these to rupture and form a crack.

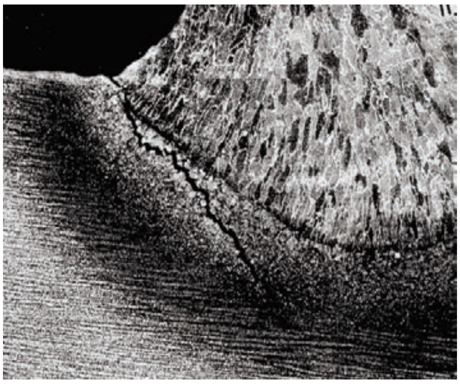
It is important not to weld on or near metal surfaces covered with scale or which have been contaminated with oil or grease. Scale can have a high sulfur content, and oil and grease can supply both carbon and sulfur. Contamination with low melting point metals such as copper, tin, lead, and zinc should also be avoided.



| Causes | Prevention |
|---|---|
| The weld metal has a high carbon or impurity content (sulfur etc) | Ensure the use of "clean" steels |
| The depth-to-width ratio of the solidifying weld bead is large (deep and narrow) | Modify welding parameters (current, voltage, travel speed etc.) to ensure correct weld bead profile |
| Disruption of the heat flow condition occurs, e.g. stop/start condition | Whenever possible, limit the number of stop / start locations |
| Scale, oil, grease or other contaminants on the plate surface | Clean surfaces thoroughly prior to welding |

### 5.4.3 Hydrogen induced cracks

**Description:** Hydrogen induced cracking is also known as cold cracking, delayed cracking or underbead / toe cracking and occurs primarily in the grain-coarsened region of the HAZ. Underbead cracking lies parallel to the fusion boundary, and its path is usually a combination of intergranular and transgranular cracking. The direction of the principal residual tensile stress can, for toe cracks, cause the crack path to grow progressively away from the fusion boundary towards a region of lower sensitivity to hydrogen cracking. When this happens the crack growth rate decreases and eventually arrests.



A combination of three factors is necessary to cause HAZ hydrogen cracking:

Tensile Stress

Cracking (at room temperature)

Susceptible microstructure

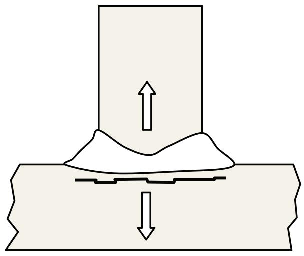
High hydrogen concentration

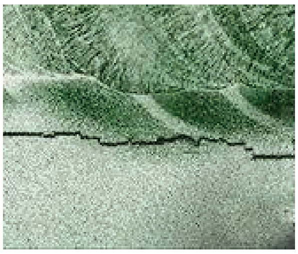
In addition, the weld must cool down to near normal ambient temperature, where the effect of hydrogen is at its maximum. If any one factor is not satisfied, cracking is prevented.

| Causes | Prevention |
|---|---|
| Too fast a cooling rate | Slow down the rate of cooling (e.g. apply preheat), thus avoiding susceptible microstructure |
| Too high a hydrogen concentration in the weld metal | Reduce weld metal hydrogen by selecting low hydrogen welding process / consumables |
| Scale, oil, grease or other contaminants on the plate surface | Clean surfaces thoroughly prior to welding |
| Complex joint configurations resulting in excessive amounts of residual stress | Blend the weld profile to reduce stress concentrations at weld toes or apply post-weld heat treatment |

### 5.4.4 Lamellar tearing

**Description:** Lamellar tearing occurs only in rolled steel products (primarily plates) and its main distinguishing feature is that the cracking has a step-like appearance as fracture progresses from one inclusion to the next at a different depth by tearing; the tearing is a ductile fracture, generally completely sub-surface and not detectable by visual examination.





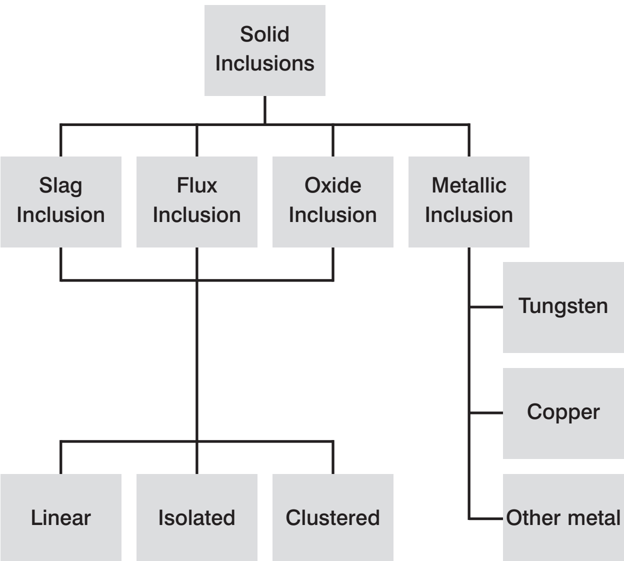
| Causes | Prevention |
|---|---|
| High thermal contraction strain in the through thickness direction of the steel | Review weld joint design, apply restraint control and adopt a suitable welding sequence |
| Excessive amount of non-metallic inclusions in the plate material | Use a clean steel with guaranteed through thickness properties |

## 5.5 Solid Inclusions

### 5.5.1 Introduction

**Description:** Solid foreign substances entrapped in the weld metal.

The following diagram illustrates the types of solid inclusions that may occur.




### 5.5.2 Slag inclusions

**Description:** Slag trapped during welding. The imperfection is of an irregular shape and thus differs in appearance from a gas pore.

| Causes | Prevention |
|---|---|
| Incomplete slag removal from underlying surface of multi-pass weld | Improve inter-run cleaning |
| Slag flooding ahead of the arc | Position work to gain control of slag. Welder needs to correct angle of electrode |

### 5.5.3 Flux inclusions

**Description:** Flux trapped during welding. The imperfection is of an irregular shape and thus differs in appearance from a gas pore. These appear only in the case of flux associated welding processes (i.e. MMA process 111, SAW processes 12 and FCAW processes 114 without gas shield and 136 with gas shield).

| Causes | Prevention |
|---|---|
| Unfused flux due to damaged coating | Use electrodes in good condition |
| Flux fails to melt and becomes trapped in weld | Change the flux / wire. Adjust welding parameters to produce satisfactory welding conditions |

### 5.5.4 Oxide inclusions

**Description:** Oxides trapped during welding. The imperfection is of an irregular shape and thus differs in appearance from a gas pore.

| Causes | Prevention |
|---|---|
| Heavy mill scale / rust on work surface | Clean / grind surface prior to welding |

## 5.6 Lack of Fusion or Penetration

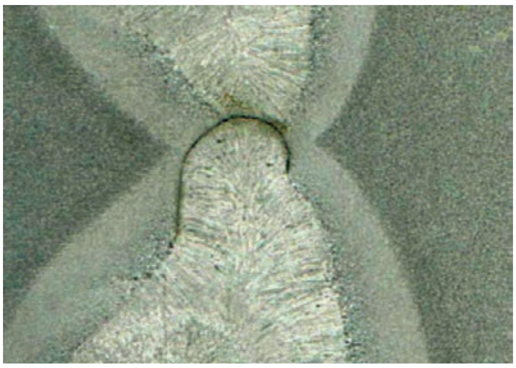
### 5.6.1 Lack of sidewall fusion

**Description:** Lack of union between the weld and parent metal at one or both sides of the weld.

| Causes | Prevention |
|---|---|
| Low weld heat input | Increase arc voltage and / or welding current; decrease travel speed |
| Molten metal flooding ahead of the arc | Improve electrode angle and work position; increase travel speed |
| Oxide or scale on weld preparation | Improve edge preparation procedure |
| Excessive inductance in MAG dip transfer welding | Reduce inductance, even if this increases the level of spatter |

### 5.6.2 Lack of inter-run fusion

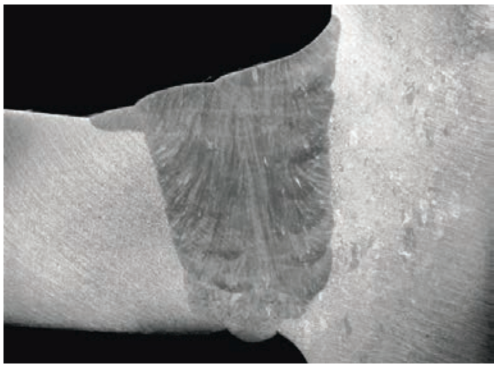
**Description :** Lack of union between the fusion lines between the weld beads.



| Causes | Prevention |
|---|---|
| Low arc current resulting in low fluidity in weld pool | Increase welding current |
| Too high a travel speed | Reduce travel speed |
| Inaccurate bead placement | Review WPS / Improve welder skill |

### 5.6.3 Lack of root fusion

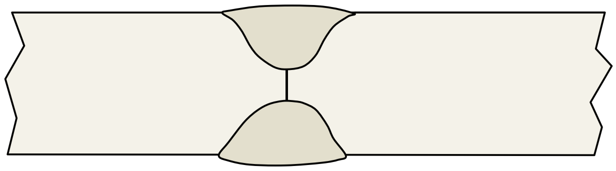
**Description :** Lack of fusion between the parent metal and the root of the weld.



| Causes | Prevention |
|---|---|
| Low heat input | Increase welding current and / or arc voltage and decrease travel speed |
| Excessive inductance in MAG dip transfer welding | Use correct induction setting for the parent material |
| Use of vertical down welding | Switch to vertical up |
| Incorrect (large) root face | Reduce root face |
| Incorrect electrode angle or manipulation | Use correct electrode angle and ensure welder is fully qualified and competent |
| Excessive misalignment at root | Ensure correct alignment |

### 5.6.4 Lack of penetration

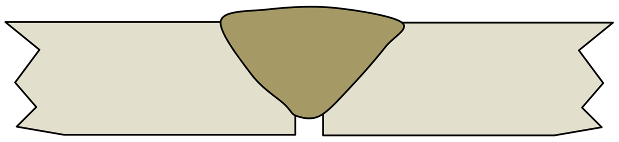
**Description:** The difference between the actual and nominal penetration.

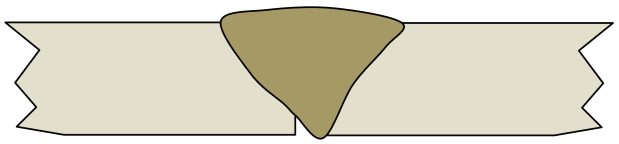


| Causes | Prevention |
|---|---|
| Excessively thick root face, insufficient root gap or failure to cut back to sound metal in a "back gouging" operation | Improve back gouging technique and ensure the edge preparation is as per the qualified WPS |
| Low heat input | Increase welding current and / or arc voltage and decrease travel speed |
| Excessive inductance in MAG dip transfer welding, pool flooding ahead of arc | Improve electrical settings and possibly switch to spray transfer |
| Use of vertical down welding | Switch to vertical up |

### 5.6.5 Incomplete root penetration

**Description:** One or both of the fusion faces of the root are not melted. When examined from the root side one or both of the root edges are clearly visible.





The causes and prevention are the same as those for lack of root fusion.

# 6 NSSS Weld Acceptance Criteria

As explained in section 3.4 of this guide, these criteria provide the fitness for purpose (FFP) basis for identifying whether weld quality is acceptable. Generally the necessary remedial action is "Repair". In some cases, however, it is necessary to "Refer to RWC". These are situations where repair by re-welding is impracticable.

| | Parameter | Weld type | Weld Orientation | | Figure reference in Table C2 | Acceptance criteria for normal quality (all dimensions in mm) | Remedial action for non-conforming welds See Note (6) |
|---|---|---|---|---|---|---|---|
| Weld geometry | Location | All | | | | D ± 10 | Repair |
| | Weld type | All | | | | D | Refer to RWC |
| | Length | All | | | | D +10 – 0 | Repair |
| Profile discontinuities | Throat thickness | All | | | (i),(ii),(iii) | a,s ≥ D (Av. 50)<br>a,s ≤ D +5 | Repair and dress smooth |
| | Leg length | Fillet | | | (i) | z ≥ D (Av. 50) | Repair |
| | Toe angle | All | Transverse or Longitudinal | | (i),(ii) | θ ≥ 90° | Repair and dress smooth |
| | Excess weld metal | Butt | Transverse or Longitudinal | | (ii) | h ≤ 6 | Repair and dress smooth |
| | Incomplete groove or concave root | Butt | Transverse | | (ii) | h ≤ 0 (Av. 50) | Repair |
| | | | Longitudinal | | (ii) | h ≤ 0.1t | |
| | Linear misalignment | Butt | Butt Joint | | (iv) | h ≤ D + 0.2t | Refer to RWC |
| | | All | Transverse cruciform | | (v) | h ≤ D + 0.4t | |
| | | | Longitudinal | | (iv),(v) | h ≤ D + 0.4t | |
| Surface breaking discontinuities | Undercut | All | Transverse (not lap joint) | | (iv),(v) | $h_1 + h_2 \leq 0.05t$<br>$l$ - No limit | Repair |
| | | Fillet | Transverse (lap joint) | | (iv) | $h_1 + h_2 \leq 0.03t$<br>$l \leq 10$ | |
| | | All | Longitudinal | | (iv),(v) | $h_1 + h_2 \leq 0.1t$ | |
| | Lack of root penetration | S/S Butt | Transverse | | (iii) | h ≤ D + 0.05t (Av. 50) | Repair |
| | | | Longitudinal | | (iii) | h ≤ D + 0.1t (Av. 50) | |
| | Porosity | All | Transverse | | (vi) | d ≤ 2<br>Σ d ≤ 10 [100] | Repair |
| | | | Longitudinal | | (vi) | d ≤ 2<br>Σ d ≤ 20 [100] | |
| | Lack of fusion | All | | | | Not permitted | Repair |
| | Cracks | All | | | | Not permitted | Repair |
| Sub-surface discontinuities | Lack of fusion/root penetration, slag lines | Butt | Transverse | Full depth | (vii) | h ≤ 3 and Σ $l$ ≤ 1.5t [100] | Repair |
| | | | | Zone O | (vii) | $l$ ≤ 10<br>$l'$ ≥ 10 | |
| | | | | Zone I | (vii) | $l$ ≤ 1.5t [100]<br>h' ≥ 6 | |
| | | | Longitudinal | Full depth | (vii) | h ≤ 3 and Σ $l$ ≤ 3t [100]<br>No individual limits on $l$ or $l'$ | |
| | Root Gap | Fillet, P/P Butt | | | | (i),(v) | h ≤ 2 (Av.100)<br>h ≤ 3 Repair |
| | Cracks | All | | | | Not permitted | Repair |
| | Lamellar Tears | All | Transverse Longitudinal | | | Not permitted | Refer to RWC |

**Abbreviated terms:**

| | |
|---|---|
| D | As specified on drawing |
| P/P | Partial Penetration |
| Repair | Repair by welding to approved procedure |
| S/S | Single sided (including butt weld in hollow section) |
| (Av. 50) | Length of weld over which measurement may be averaged (mm) |
| [100] | Length of weld over which summation is made (mm) |
| *l* | Length of discontinuity - parallel to the weld axis |
| *l'* | Gap between ends of discontinuities - parallel to the weld axis. If non-conforming, *l* becomes the overall length of the discontinuities plus the gaps(s) between them. |
| h | Height of discontinuity - in thickness direction |
| h' | Gap between discontinuity - in the thickness direction |
| I | Inner zone |
| O | Outer zone |

**Notes:**

(1) For definition of orientation see Annex B.

(2) Thickness applies to minimum member thickness at weld in question.
For thickness greater than 20mm 't' shall be taken as 20mm.
The limiting value 'h' for any discontinuity, where related to member thickness 't', is the greater of this calculated figure or 0.3mm.

(3) "Lap" shall apply to any fillet welded attachment whose length in the longitudinal direction exceeds 50mm.

(4) Subject to any other locational requirements.

(5) Where more than one requirement is given both shall apply.

(6) Where a repair is necessary an approved procedure shall be used. If on increasing the scope of inspection, further non-conformances are found, the scope shall be increased to 100% for the joint type in question.

(7) Lamellar tears may be accepted in the longitudinal welds only if extent does not exceed limits for lack of fusion in transverse welds.

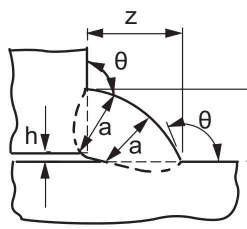



Figure (i)

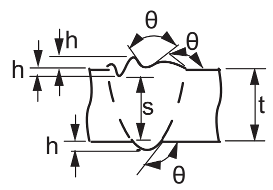



Figure (ii)

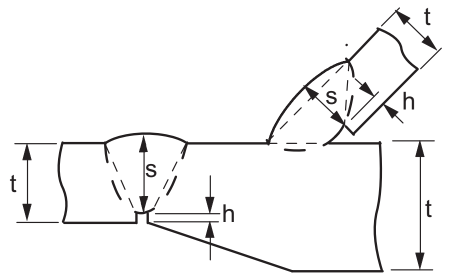



Figure (iii)

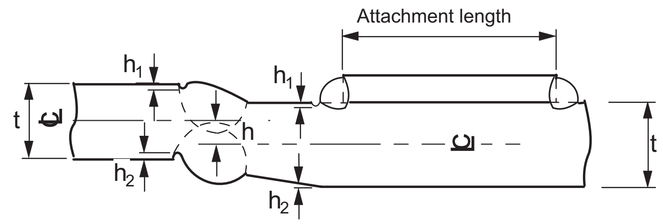



Figure (iv)

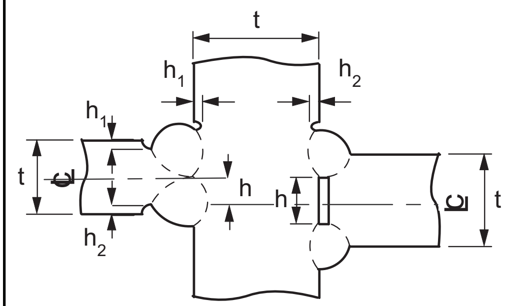



Figure (v)

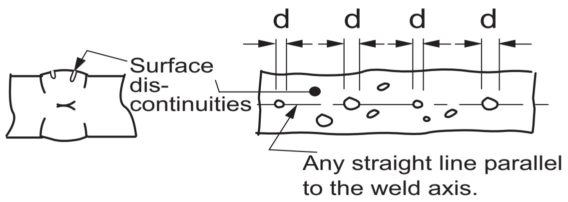



Figure (vi)

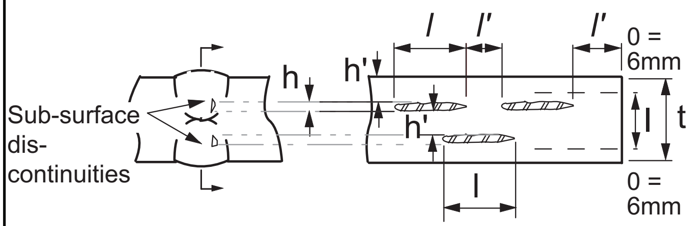



Figure (vii)

Sub-surface discontinuities may be in Zones I (as shown) or O

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