

**ELECTRON BEAM
WELDING
BEST PRACTICE GUIDE**



EBP

**Electron Beam Processes Ltd
Europe's most experienced
EB Welding specialist**

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Electron Beam Processes Ltd pioneered the concept of providing an EB Welding service to industry in 1966 and have since established an enviable reputation, with a customer base covering a wide sector of the engineering field and whose applications range from Aerospace to sub-sea equipment and Formula 1 racing to medical components.

Not surprisingly, technical problems arise from time to time, particularly with work for a company who may not have had previous experience of EBW as a process. Invariably however, in such cases the problem can be linked to one or more of the **following causes**:-

- The selection of a material specification or condition unsuitable for welding.
- Incorrect joint design.
- Incorrect machining preparation.
- Assembly of parts in a contaminated condition.

As welding specialists we naturally wish to ensure that these pitfalls are avoided and will readily advise on any aspect of the design and machining of a component in order to get things off to a good start.

Obviously, the best time to input our advice is at an early design stage rather than as the parts are leaving the machine shop! A telephone call, or a sketch by fax or e-mail, outlining the problem is all that is needed for us to establish that the scheme is viable as planned, or would benefit from a design change.

The object of this brochure is to give 'best practice' guidelines on those aspects of the preparation of parts for EBW that have a direct bearing on the quality of the welded component. Our aim, like yours, is to produce a welded fabrication that fully meets the design criteria.

Selecting weldable materials

When designing a component as a welded fabrication it may be necessary to compromise between opting for the ideal mechanical properties of a material and choosing another specification that has better welding properties. A grade of steel normally used for a cast component for example, would not be the obvious choice for a welded fabrication.

These notes outline the factors that determine the weldability of some of the metals most commonly employed in EBW application, but are intended as a guide rather than a complete listing of all weldable material specifications.

If in any doubt therefore, 'consult the welder before cutting metal'!

Steels

Low carbon, case hardening and austenitic stainless steels are generally weldable as are most nickel and copper base alloys.

It is important to note that free cutting grades should not be specified for welded fabrications; the lead and sulphur additions so helpful to the machinist act as a contaminant and can adversely affect weld quality.

Case hardened components must be free of case in the immediate weld area. In practice, this means that the joint faces and adjacent surfaces within 3mm of the joint should either be masked off during the hardening operation or, have the case removed locally afterwards.

High carbon, direct hardening steels need careful selection as the welding operation hardens the joint area. The degree of hardness varies with the composition of the alloy and in general, the higher carbon grades become crack prone and difficult to weld satisfactorily.

Aluminium Alloys

The low and medium strength grades weld satisfactorily but the higher strength alloys are crack prone, primarily due to their higher copper content.

The availability of a wide range of extruded tube, bar and plate sections has resulted in EBW becoming a popular method for fabricating precision machined components of all descriptions as an alternative to casting, forging or machined from solid.

Exotic Metals

Titanium alloys are ideally suited to a welding technique carried out in vacuum and, with the limited range of stock sections available, the ability to fabricate complex components by EBW opens up interesting design possibilities. Hastelloy and Nickel based alloys such as Inco 625 & 718 all EB weld with great success.

Other refractory metals are less commonly used in general engineering and of these, Molybdenum and Zirconium are weldable but Tungsten is very crack prone.

Dissimilar Metals

Dissimilar metals that are weldable include low carbon and stainless steels to each other and to copper and nickel base alloys. Aluminium and refractory metals generally cannot be joined satisfactorily to other materials by EBW.

Joint Design

The machining preparation for EBW is very straightforward; the basic requirement being for the joint to simulate 'solid' metal in the path of the electron beam.

The need for closely fitting joints can be better appreciated when it is realised that no filler material is used in beam welding (except for special applications) and consequently, it is essential to have good fit conditions.

The key features of a well prepared EBW joint are:-

- Joint faces to be in close abutment, e.g. a gap in the order of 0.05mm (0.002") is acceptable when welding a 10mm section but should be less for a thinner joint.

Turned parts fall into two categories, having either circumferential or planetary joint configurations and these have different fit requirements:-

Circumferential joints are typically used to attach a flange, or gear, to the end of a shaft with a spigot serving to hold concentricity and also to make the assembly self-locating. In this case a slight clearance fit is needed on the spigot diameters allowing the component to be 'cold' assembled.

For planetary joints, i.e. the joint running around the axis of the shaft, a size/size to slight interference fit is required to compensate for shrinkage which occurs in the weld. A good rule of thumb is to allow an interference of 'one thou per inch' of joint diameter (0.025mm per 25mm diameter) up to a maximum of 0.125mm.

- The machining preparations for welding components with linear welds are illustrated overleaf and include plain, spigotted butt and lap joints. The same standards apply however; joint faces should be machined true and square to give close abutment on assembly.
- The use of chamfers should be avoided as these simply reduce the effective weld section. When it is necessary to relieve a sharp corner it is better to use the instruction 'break edge'. With spigot preparations it is important that the corner radii on each mating part do not prevent the joint faces from abutting on assembly.
- Joints should be located in clear 'line of sight' of the beam i.e. clear of any projecting flange or buttress features. Normally a clearance of 3mm is sufficient but a greater clearance is required where a projection stands well above the joint surface e.g. as in the case of a large gear assembled onto the end of a much smaller diameter shaft.

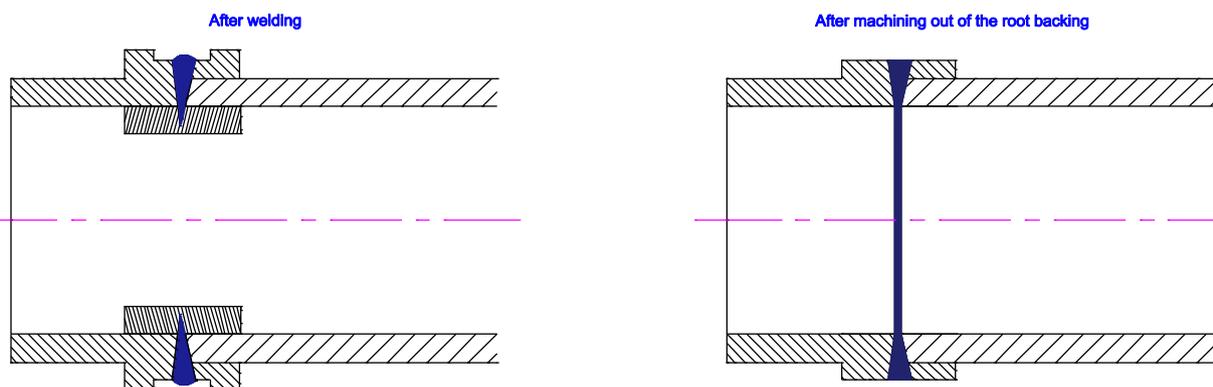
Full penetration welds

The advantages of full penetration weld joints are that they:

- Increase the strength of the joint
- Are easier to inspect than partial penetration welds
- Contract more symmetrically during solidification than partial penetration welds
- Tend to have fewer defects than partial penetration welds

Weld preparations for full penetration welds may be simpler and less expensive to machine than those for partial penetration welds. If joints cannot be made self-locating, very close attention must be paid to the fit-up, fixturing and tacking in order to achieve correct alignment and good final tolerances. If a full penetration weld is required, but there are concerns that the final tolerances may not be achieved using a full penetration weld joint, a slightly deeper, self-aligning partial penetration weld can be used and the excess un-welded section machined off after welding, if possible. For circumferential full penetration assembly, welding with root backing (usually metallic cylinder metallurgically compatible with the welded materials) must be employed if spatter and undercutting are to be avoided. A post-weld machining step is necessary to remove the backing piece. This may not always be possible depending on the oval design of the tool and the manufacturing stage at which the EB welding occurs.

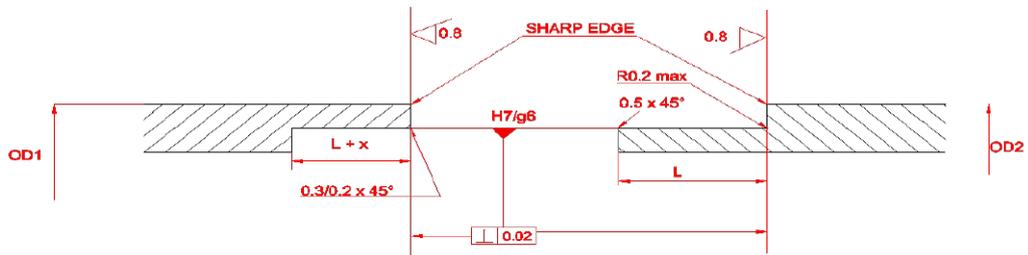
Such a process must be validated during WPS approval, and indicated in the WPS.



Example of a full penetration weld with a temporary backing

Partial penetration welds

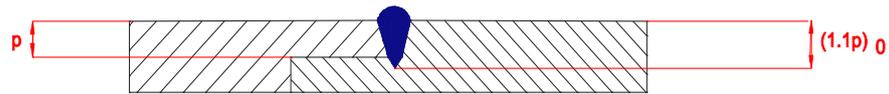
Many EB weld design applications require partial penetration welds. This is mainly because welds are often used to assemble end pieces or covers to a main body that contains sensitive electronic and non-metallic parts. The relatively low heat input allows EB welds to be used in this way. With partial penetration the joint design can often self-locate the parts improving alignment and reducing or eliminating post-weld machining.



Recommended shapes for fitting of parts

Length of mating spigot (L) $\geq OD/4$ and \leq Fitting diameter \times (minimum play of fitting)/0.04
 x must be $>$ the estimated weld shrinkage

The fitting thickness is depending on the conception needs; however it must be greater than the maximum weld penetration



Sectioned drawing of assembly after welding.

The weld penetration depth must be stated with a tolerance: $0.1p$ with a minimum of 1mm
 Geometric and dimensional tolerances must be specified as "After welding"

Short fitting

Design constraints may limit the overlap. In such cases, the location spigot will only ensure the concentricity of the assembly. The straightness may be ensured by the use of suitable fixtures keeping the weld faces together.

Locating the joint

It may be necessary to include features that assist in locating the joint prior to and after welding, ideally this should be reviewed and agreed with EBP Limited.

The options for such features are:

- A specified tolerance dimension between the joint and a machined feature that is accessible after welding. This is readily applicable to small and medium-sized parts as a preferred solution.

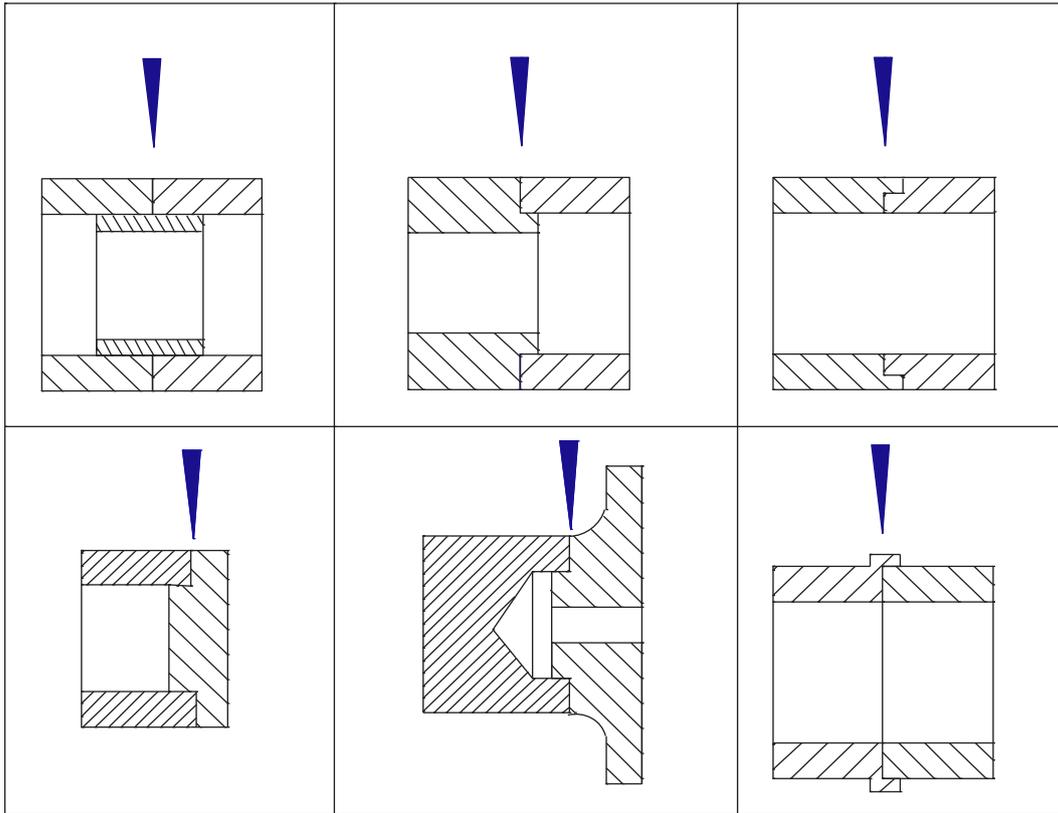
Reference lines on one or both sides of the welds. Note that reference lines with sharp corners can act as stress risers and therefore rounded corners are preferred

Tacking, clamping and fixtures

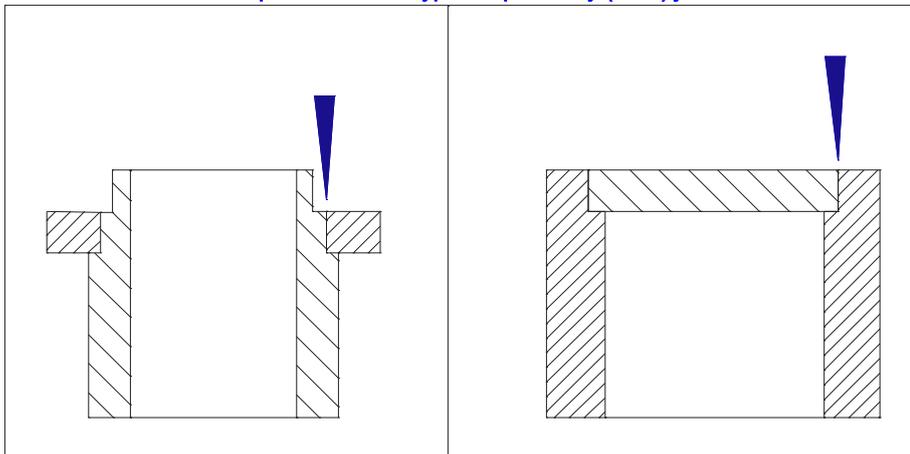
In the case of EB welding, all materials used for clamping and fixtures should be non-magnetic or de-magnetised prior to use in order to avoid any risk of the deflecting beam. The part numbers of any specific tooling must be recorded on the weld parameter data card.

Tacking can often be used to simplify clamping and fixtures. Tacks may also be essential to keeping the joint in close contact throughout the welding process. Tacks may be EB or T.I.G. welds of short segments, spots or even a shallow seal pass. Since the tacks will be incorporated into the weld joint they must be of high quality and must also be included in the welding specification and qualified with the weld procedure. The tacking process can create some distortion, and tacks are therefore essential parameter of the WPS.44

Examples of circumferential (radial) assemblies designs with centering

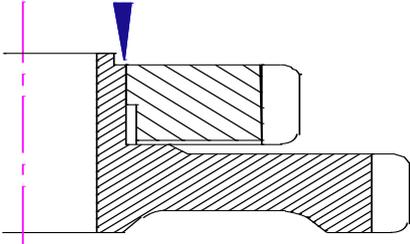


Examples of various types of planetary (axial) joints

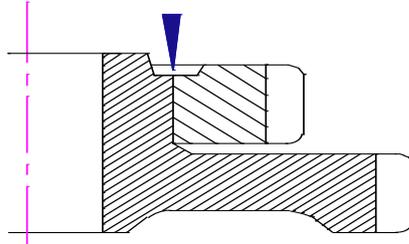


EXAMPLES OF GOOD ASSEMBLY PRACTICE (EN 1011-7)

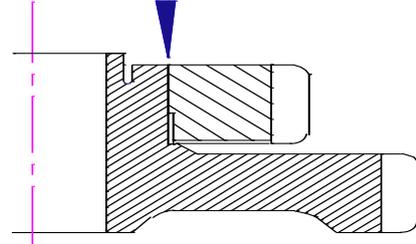
Gear welded assemblies



Gear wheel with unsuitable located axial joint. The joint is too close to the central bore.

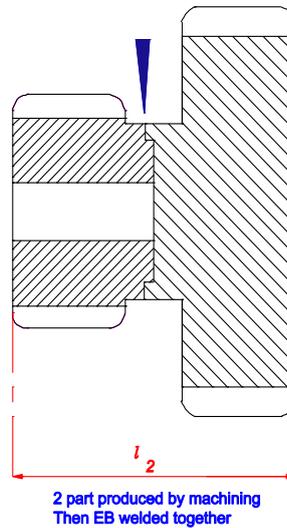
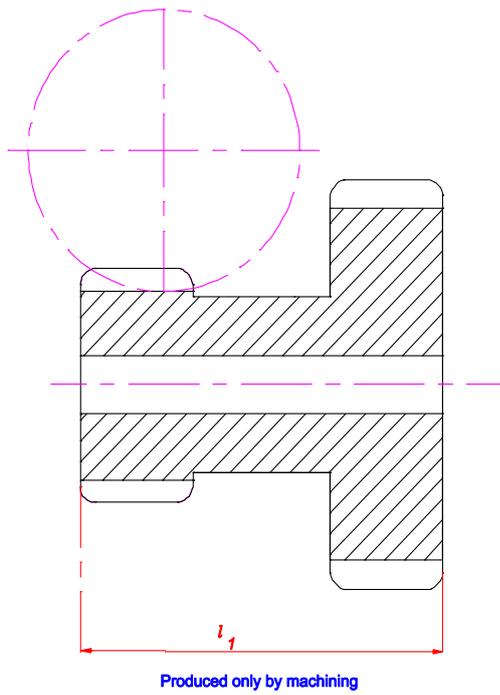


Improvement 1: The joint is further from the central bore and the wall thickness has been adapted to suit the required weld

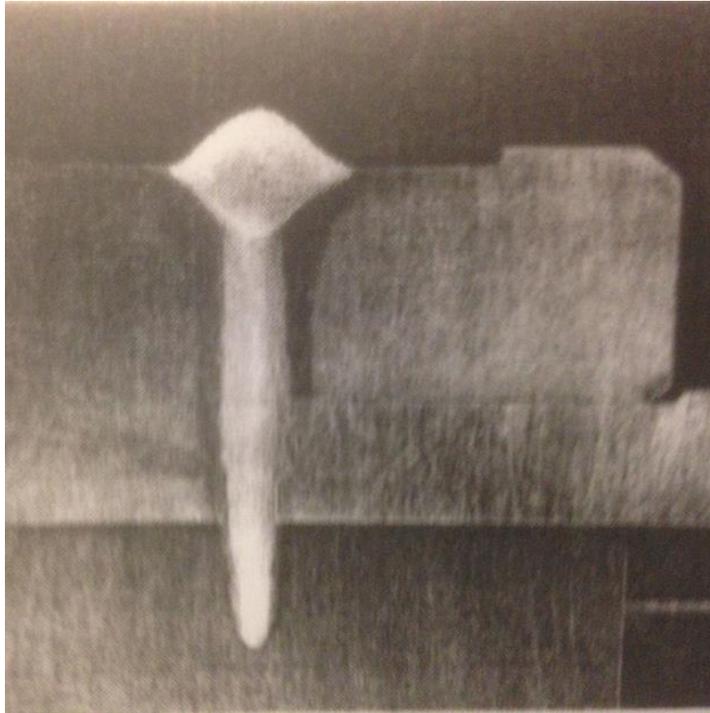


Improvement 2: The slot has been included to accommodate radial shrinkage.

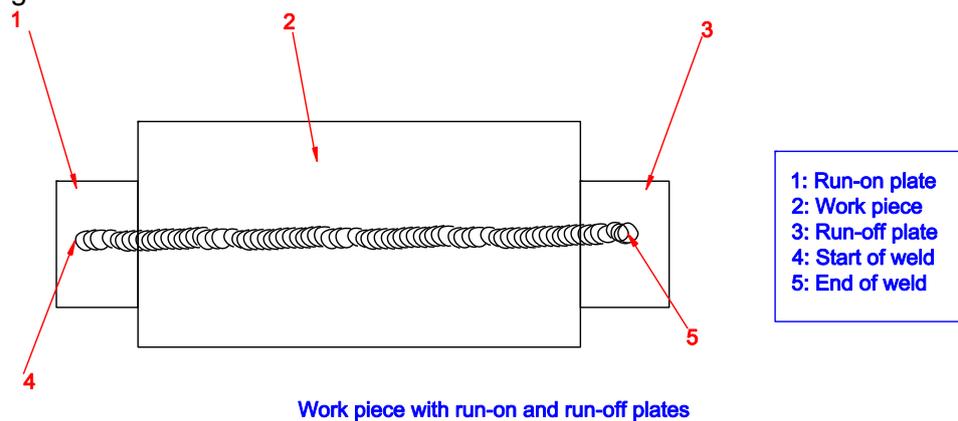
Length Reduction



Linear Welds



For linear seams, to eliminate the end crater, run-on and run-off pieces should be used. These must be the same material and clamped or tack welded in position and removed by post weld machining



Work piece with run-on and run-off plates

Weld shrinkage

Regardless of whether joints are full or partial penetration, joint design must take shrinkage into account. If the design does not allow uniform shrinkage of the weld metal, cracks can form, especially in high yield strength materials.

For all welds, the amount of shrinkage relates to the weld cross-section as follows:

$$\text{Transverse shrinkage} = k A/t$$

Where:

K = empirical factor between 0.1 and 0.17, usually 0.1

A = weld cross-sectional area (fused area)

t = weld thickness

For full penetration butt welds, this can be simplified as:-

$$\text{Transverse shrinkage} = k \times \text{average width of the weld.}$$

More elaborate equations are available, but for single-pass welding (which is the case of EB welding) the equations above are useful for quick predictions and comparisons. For longitudinal welds, transverse shrinkage will reduce the width across the joint. This will also happen in circumferential welds, but the diameter will also be reduced to some extent. The raised profile of the cap and root of most EB welds are due to the transverse shrinkage.

The behaviour of the qualification test assembly will give a very good indication of the weld shrinkage that will occur in the final assembly. The oval length before and after welding should be noted during the qualification procedure.

Machining

EBW is a precision welding process that allows parts to be joined with minimal distortion and free from oxidation effects. It follows therefore, that the pre-weld machining should also be to a good standard if close dimensional tolerances are to be achieved on the finished component.

From the machinists viewpoint however, it is not at all difficult to meet these requirements, as the joint configurations used are basically very simple turning or milling operations. In fact, the part may have been designed as a welded fabrication in order to make the machining easier.

The key features to be observed when machining are:-

- A 1.6 μ mRa (63 μ in CLA) surface finish is satisfactory for EBW joints.
- Machined parts should not be tumbled or vibro-deburred.
- Free cutting grades of steel should not be used for welded components – the lead and sulphur content causes porosity and cracking defects.

- When machining aluminium alloys of thick section it is good practice to make the finishing cut on joint faces 'dry' i.e. without cutting lubricants, as these are very difficult to remove at the pre-weld cleaning stage.
- In machining locating spigots, corner radii should be relieved just enough to ensure that the joint faces are not prevented from fully closing on assembly. Chamfering however, should be discouraged as this can result in the creation of an air trap within the joint and result in weld porosity defects. So it is always safer to use the term 'Break edge' rather than 'Chamfer'.
- Parts which have planetary joint preparations, e.g. a gear fitted to the end of a stub shaft, require a size/size to slight interference fit condition, in order to compensate for contraction which occurs in the weld. (Refer to the section on 'Joint Design' for dimensional details).
- Where external spigot preparations are used it is helpful to the welder if a machine mark is made on the O/D to indicate the true joint position. (A simple method is to skim 0.010" (0.25mm) off the O/D up to the joint location).
- For new applications we typically need three sets of test pieces (or scrap components) for establishing welding parameters. These are then recorded and applied to all future production batches.

It is very important that the test pieces fully simulate both the material specification, joint cross-section and local mass of the actual component.

- Finally, the 'as machined' components should not be assembled prior to despatch for welding. A pre-weld cleaning operation (and a demagnetising stage for ferrous parts) is normally carried out by the welder just before processing.

Preparation and Assembly

EB Welding is carried out in vacuum and as a result, the process allows parts to be joined without any adverse oxidising effects. It follows therefore, that the components should be free of any contaminants, such as cutting lubricants, anti-rusting oils etc. when they are assembled for welding. Hence, the pre-weld preparation stage is all-important to the success of the operation and it is for this reason that the pre-weld assembly is normally undertaken by the welder, working to the following procedure:-

- Before components are released for welding a check is made to verify that they conform to the latest drawing issue.
- It is also very important that clear assembly instructions accompany the work sent for processing; remember, the welder is probably unaware of the function of the component – one 'widget' looks much like another – and if something can be put on back to front, sooner or later it will be!
- Parts must be thoroughly degreased before assembly, either by vapour or hot detergent, and the joint faces abraded and Acetone washed.

- For parts that need to be assembled by shrink fitting, e.g. planetary joints having interference fits, the procedure is to warm the outer and chill the inner section, to allow assembly to be carried out without risk of seizure.
- Ferrous components need to be demagnetised to avoid deflection of the electron beam by stray magnetism.

EBW is a process in which the welding parameters are closely controlled and recorded at the initial development stage so that on subsequent production runs each batch is welded to precisely the same settings. It is essential therefore, to notify the welder of any modification that may affect the welding operation.

A change in the material specification, or an alteration in the joint section, may make it necessary to redevelop the machine settings.

EB welding quality control

Weld Integrity - EB Welding is essentially a machine-controlled process in which precise parameters can be determined at the development stage and logged for future use in the production of the component.

The EB weld process is a vacuum remelt of parent materials, providing parts are thoroughly clean and correctly fitted, results are highly respectable and of excellent quality.

Hence, providing that the weld development is designed to accurately simulate the physical geometry and material specification of the actual component the results achieved on the test pieces will be repeatable within very close tolerances on the production components.

Non-destructive testing of EB welds is a subject in its own right but a brief summary of the principal NDT methods used should be included:-

1. Visual Inspection - All welds are visually inspected using x 10 or greater magnification as necessary. Surface defects e.g. cracks, mis-alignment, under penetration or undercutting can usually be detected by this method.
2. Penetrant Crack Detection - Normally the water washable fluorescent dye technique is used to identify possible surface defects that may not be readily seen by visual examination.
3. Radiography - Where the component joint geometry permits, an X-ray examination technique can identify sub-surface defects that would be hidden from the Visual and Penetrant Inspection methods. In particular, internal porosity and crack defects can be identified and recorded on film. Radiography is, however, a relatively expensive NDT technique and for this reason is sometimes used on a sample basis, typically 10% of the batch of components welded.

4. Ultrasonic Testing - Subject to component geometry, Ultrasonic testing can provide a cost effective and reliable method for detecting internal weld defects. Results can be assessed against a go/no go setting and printed to provide a permanent record.
5. Pressure or Vacuum Leak Testing - These provide, again subject to component configuration a performance test of individual components.
6. Batch Control Test Pieces - Test pieces directly simulating the component weld and material condition can be used for quality control and can be run either before, after or during the production batch. They provide the opportunity for NDT and macro and micro section examination.
7. Process Control Specification - ENISO now offer process control and acceptance criteria specification. EBP has its own specification for weld acceptance criteria, EBP/QAS/01 Iss. 2. which is available on request.

We are sure that your introduction to electron beam welding will get off to a good start by following these ground rules and hopefully encourage you to ...

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**‘Design Electron Beam Welding into your next product to
save Cost, Size, Weight and Lead Time’**

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