Education and Culture

Leonardo da Vinci

Course: Quality Assurance

Module 6

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MODULE 6

Objective:

Know the effect of welding in terms of shrinkage, residual stresses and distortion. And know how to minimise distortion before, during and after welding.

Scope:

- ***The thermal cycle in welding***
- ***Development of residual stresses due to solidification, cooling and shrinkage***
- ***Effects of restraint on residual stress***
- ***Significance of residual stress***
- ***Preheating, postheating***
- ***Relationship between heat input and shrinkage, residual stress and distortion.***
- ***Development of distortion; effect of heat input, weld size, penetration, and number of runs single- and double-sided fillet welded joints and in butt welds.***
- ***Corrective measures, procedure, welding technique, sequence, joint preparation, pre-setting***
- ***Correction of distortion after welding***

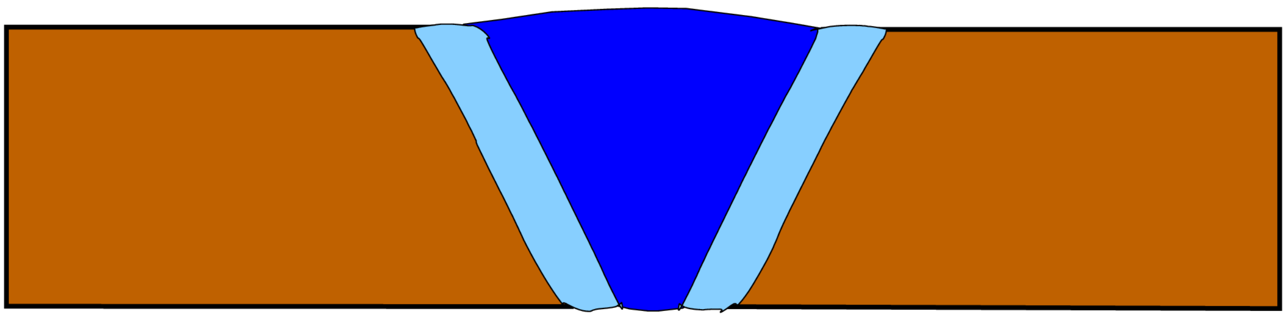
Expected results:

- ***Describe the thermal cycle during welding.***
- ***Describe distortion resulting form shrinkage.***
- ***Describe residual stresses.***
- ***Name measures to minimise distortion.***
- ***Describe the main causes for weld shrinkage.***
- ***Outline the main effects on a weld due to residual stresses.***

Control over the weld distortion

Beginning welders and even those that are more experienced commonly struggle with the problem of weld distortion, (warping of the base plate caused by heat from the welding arc). Distortion is troublesome for a number of reasons, but one of the most critical is the potential creation of a weld that is not structurally sound. This paper will help to define what weld distortion is and then provide a practical understanding of the causes of distortion, effects of shrinkage in various types of welded assemblies and how to control it, and finally look at methods for distortion control.

Distortion in a weld results from the expansion and contraction of the weld metal and adjacent base metal during the heating and cooling cycle of the welding process. Doing all welding on one side of a part will cause much more distortion than if the welds are alternated from one side to the other. During this heating and cooling cycle, many factors affect shrinkage of the metal and lead to distortion, such as physical and mechanical properties that change as heat is applied.



If we cut through a welded connection and investigate the material, we can, when simplifying, say that the connection contains three zones:

A. The parent metal which is not influenced by the welding, here shown in brown colour.

B. The heat affected zone, here shown in light blue colour

C. The weld metal, here shown in blue colour.

Zone B and C are of course not so clearly defined in reality because the mixing of molten material takes place and the structural transfer is a gradual change of structure, but for the understanding of the heat distortion itself this does not play a major role.

When a metallic material is heated it will expand in all directions. We can illustrate this as shown in figure 1. The material elements can be visualized as a cube. Before the heating the cube will have a dimension/size as shown in blue. After heating the dimension /size will expand to the yellow boundaries.

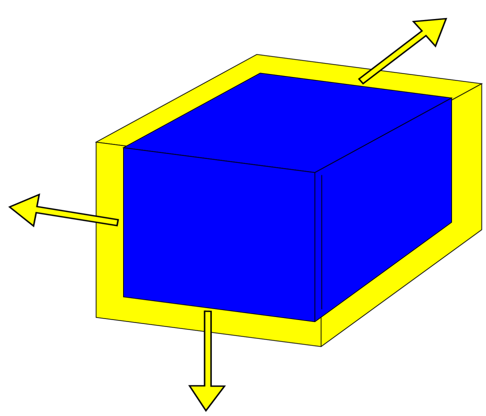


Fig 1. A material with a given dimension/size is heated and it will expand in all directions. If a steel bar is

uniformly heated while unrestrained, it will expand in all directions and return to its original dimensions on cooling.

However, in welding the heating will be locally causing the surrounding cold material to limit the free thermal expansion. In figure 2 this is illustrated by showing blue arrows, or forces , that will limit the free movement of the material.

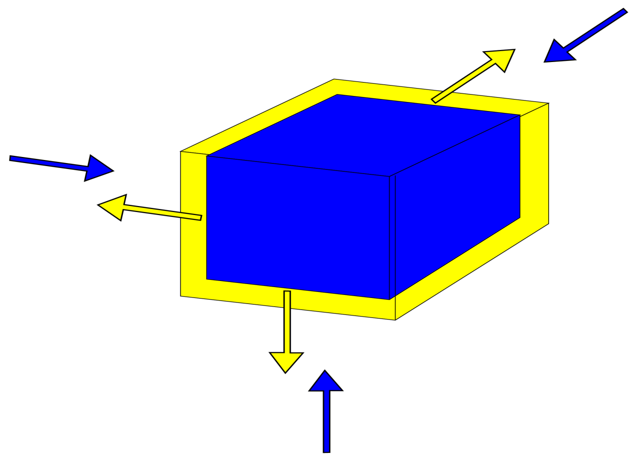


Fig 2. The material will try to expand in all direction during heating. However the cold surrounding material will try to limit the expansion. It is restrained, during heating, and will have a limited expansion. On cooling, the deformed bar contracts uniformly, and is permanently deformed.

The forces of the surrounding material will cause the internal material structure to be pressed together during the heating process. Or we may say that the distance between the smallest structural material elements will be reduced. When the material then cool down, the distance between the smallest structural elements will be kept, causing the cube to be shortened as shown in the white cube in figure 3.

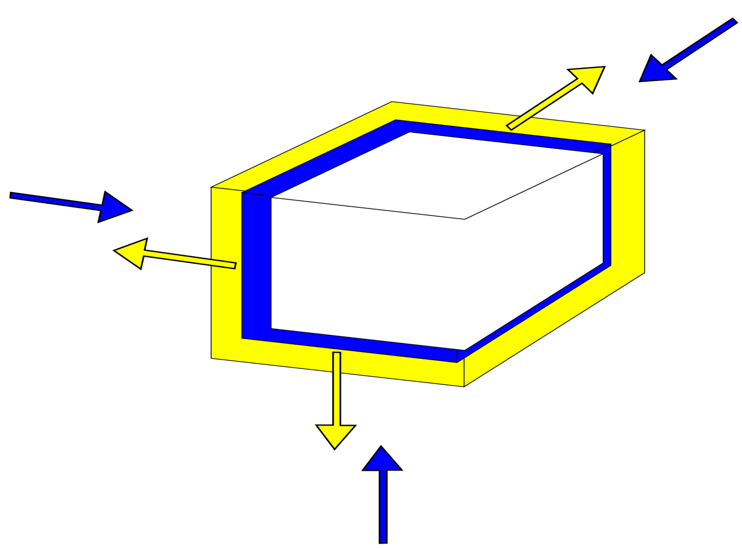


Fig 3. When cooling down the original material will be shortend of the external forces from the cold material which press the expanded material together. The resulting cold dimension/size is here shown in white.

However, during the cooling process, the hot material will will shrink and try to drag the surrounding cold material in the direction it shrinks. The surrounding material must then follow , unless it cracks, causing deformations to appear.

In a welded joint, these same expansion and contraction forces act on the weld metal and on the base metal. As the weld metal solidifies and fuses with the base metal, it is in its maximum expanded from. On cooling, it attempts to contract to the volume it would normally occupy at the lower temperature, but it is restrained from doing so by the adjacent base metal. Because of this, stresses develop within the weld and the adjacent base metal. At this point, the weld stretches (or yields) and thins out, thus adjusting to the volume requirements of the lower temperature. But only those stresses that exceed the yield strength of the weld metal are relieved by this straining. By the time the weld reaches room temperature - assuming complete restraint of the base metal so that it cannot move - the weld will contain locked-in tensile stresses approximately equal to the yield strength of the metal. If the restraints (clamps that hold the workpiece, or an opposing shrinkage force) are removed, the residual stresses are partially relieved as they cause the base metal to move, thus distorting the weldment.

The result will be that very strong forces appears and “drag” the cold material in the direction of the heated zone and we will consequently get a heat deformation.

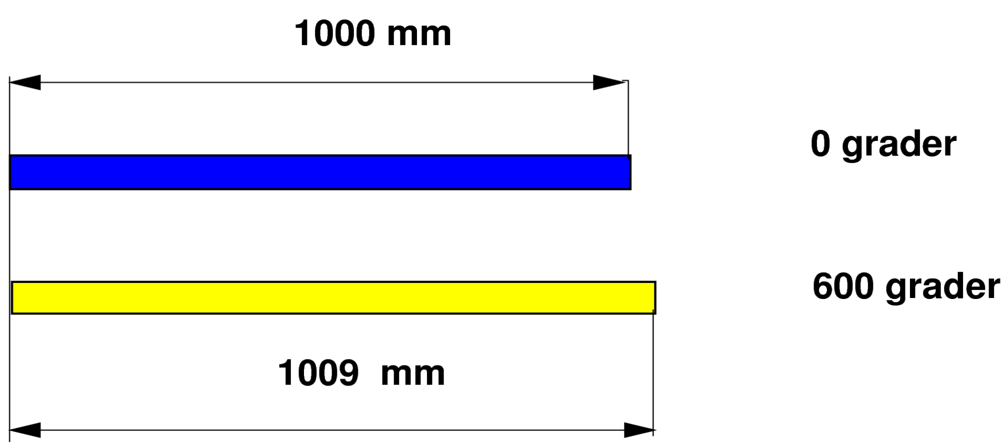


Fig 4. The figure shows how much steel will expand when it is heated from 0 degree to 600 degrees.

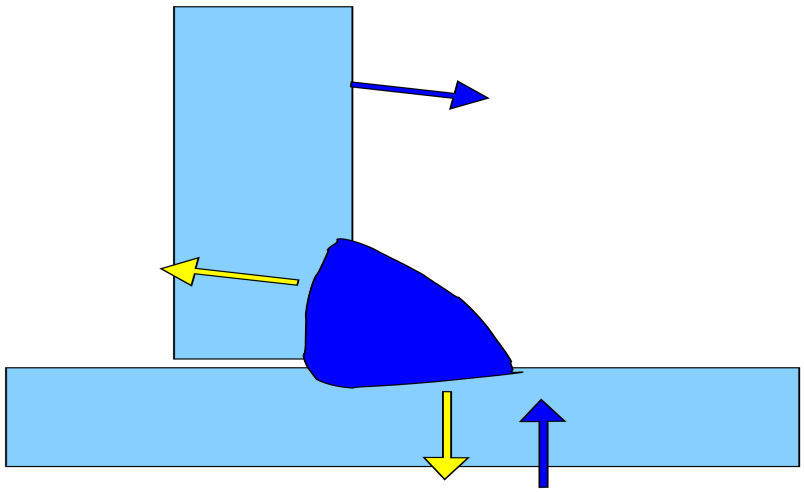


Fig 5. Fillet weld. During heating the forces will go in the direction of the yellow arrows. However the reaction forces from the cold material will cause the molten structure to shrink. The cold material gives reaction forces as shown with the blue arrows. Cooling down causes the material to bend as shown in figure 6. V

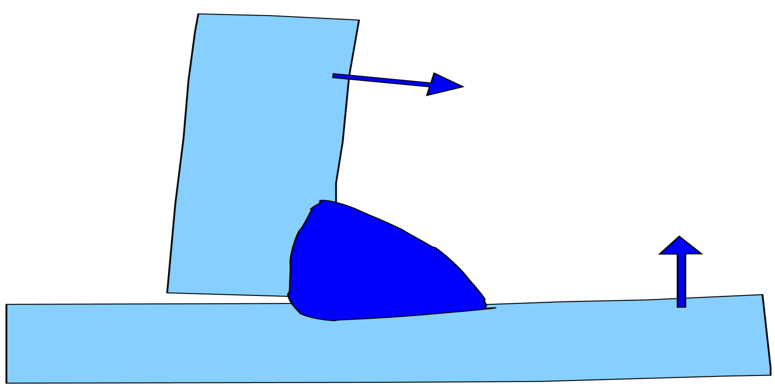


Fig 6. The geometrical form of the fillet weld after cooling down.

A butt weld gives the same problem as we had in a fillet weld. When heating the molten material will try to expand in the direction of the yellow arrows. Due to the reaction forces from the cold material the size of the molten material will shrink during the cooling process. The final result when the material cools down is that the surrounding cold material will be bent in the direction of the blue arrows.

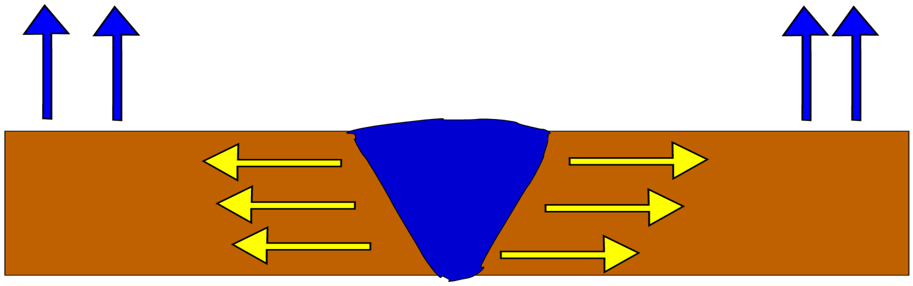


Fig 7. A butt weld. During the cooling process the material will bend in the direction of the blue arrows. The design of the bevel causes more molten metal in the top of the bevel than in the bottom of the bevel, resulting in stronger contracting forces at the top.

If we draw this in another perspective, the plate will look like this.

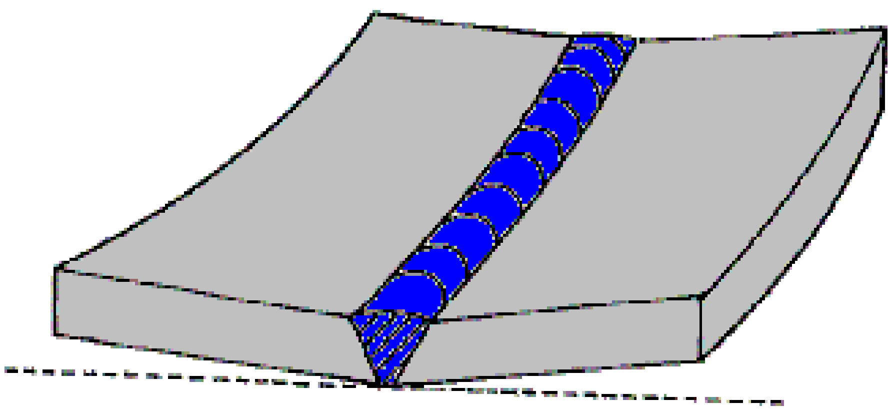


Fig 8. We see a straight surface, indicated by the dotted line. We also clearly see how the edges of the plate have been moved upwards caused by the forces earlier described..

In more complex designs and structures, you have to evaluate the heat distortion of each element and see how these elements fits together.

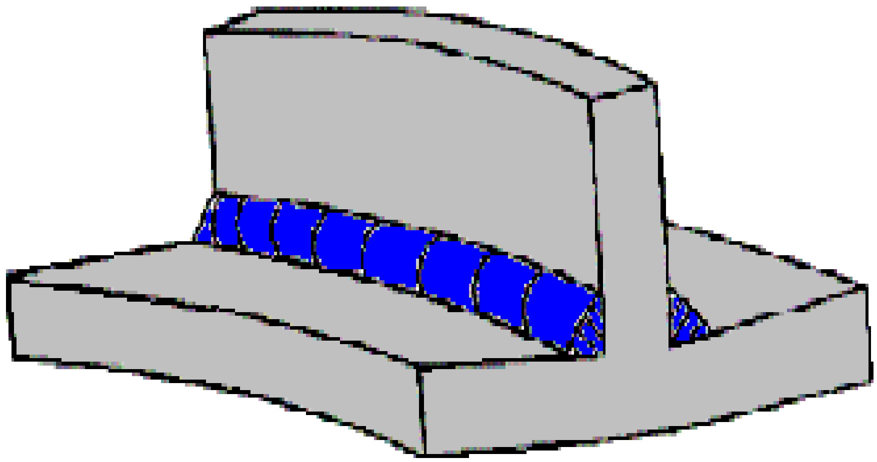


Fig 9. In this T-joint we see that the flange is bent as shown in the previous figures. In addition the leg will get a separate heat distortion and bed as shown. The resulting forces will create a structure as shown here in this drawing.

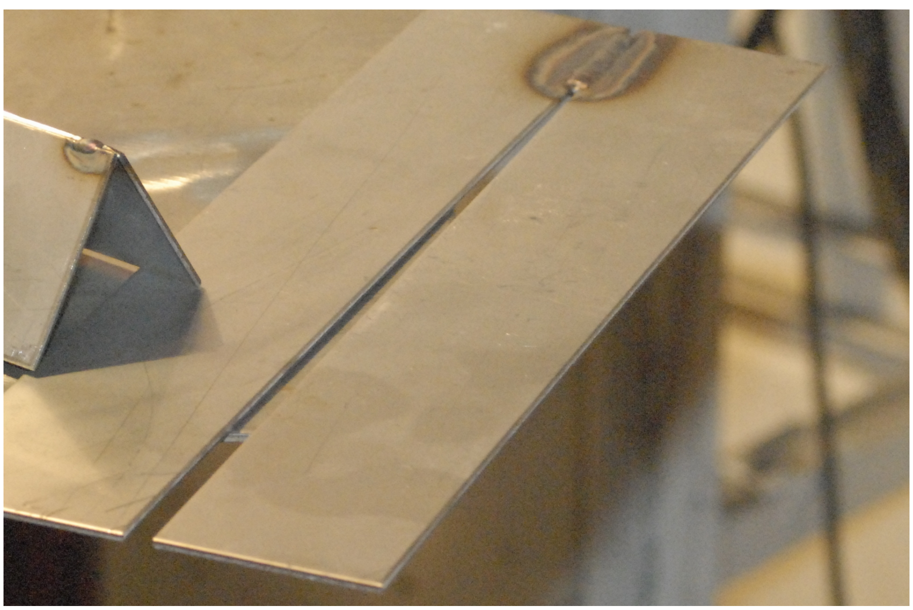


Fig 10. The figure shows the results of the heating of the material just at the end of the welding process. We see that the root opening has increased dramatically due to the heat influence.

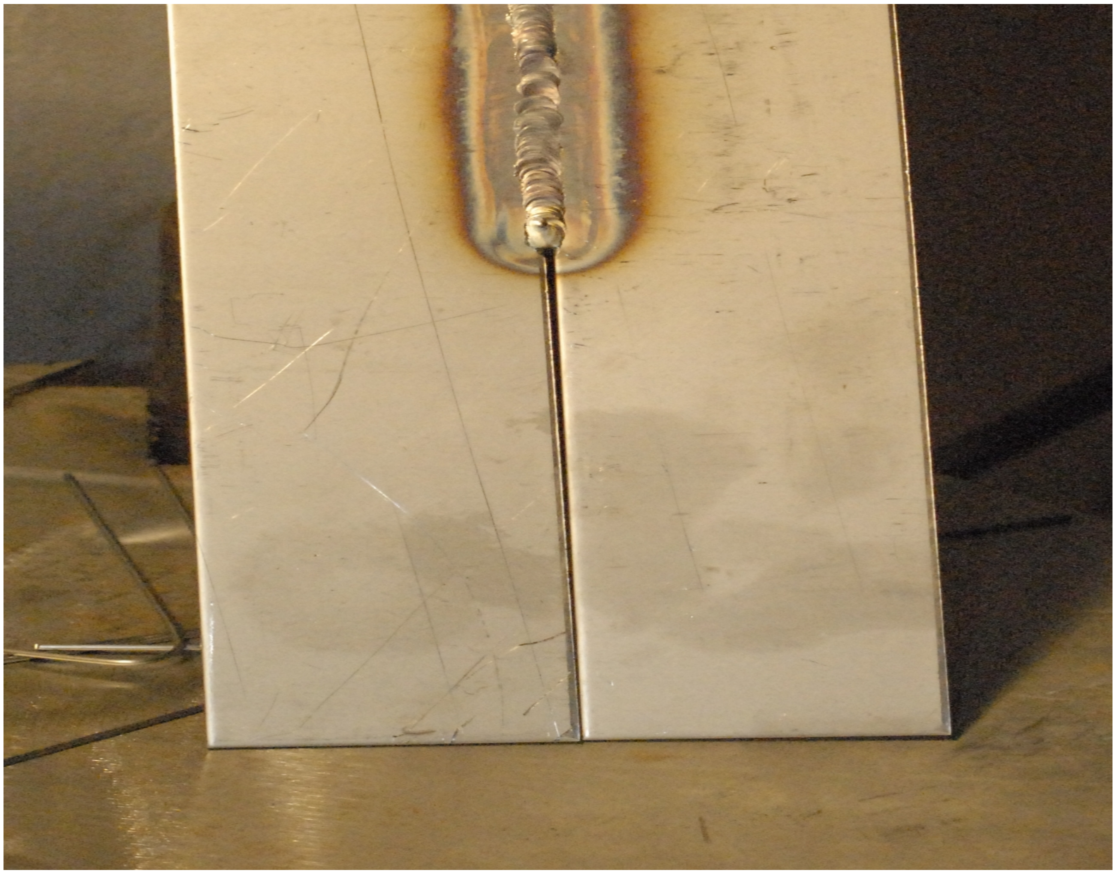


Fig 11. This photo is the same as fig 10, but show the joint connection after the cooling. We see that the bevel opening has been completely closed. This is due to the contracting forces during the cooling process.

For buttering and cladding the forces will be the same as for a standard butt weld. After welding with heat input followed by the cooling process, the material will be bent in the direction of the blue arrow.

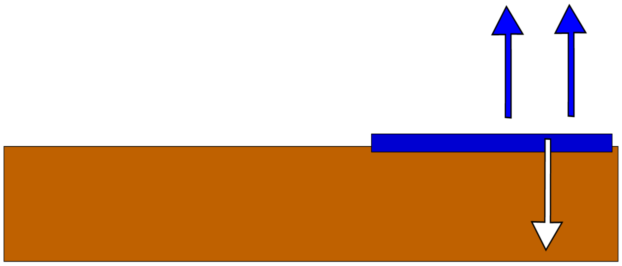


Fig 12. A cold weld where we see that the heat from the welding process goes in the direction of the white

arrow. The consequtive cooling process causes the material to bend in the direction of the blue arrows.

Fig 13. A photo of a clad weld as described above. A 3 mm rod has been rolled under the plate which has bent upwards.

How can we prevent heat distortion ?

To prevent or minimize weld distortion, methods must be used both in design and during welding to overcome the effects of the heating and cooling cycle. Shrinkage cannot be prevented, but it can be controlled. Several ways can be used to minimize distortion caused by shrinkage:

Do not overweld.

The more metal placed in a joint, the greater the shrinkage forces. Correctly sizing a weld for the requirements of the joint not only minimizes distortion, but also saves weld metal and time. The amount of weld metal in a fillet weld can be minimized by the use of a flat or slightly convex bead, and in a butt joint by proper edge preparation and fitup. The excess weld metal in a highly convex bead does not increase the allowable strength in code work, but it does increase shrinkage forces.

When welding heavy plate (over 25 mm thick) bevelling or even double bevelling can save a substantial amount of weld metal which translates into much less distortion automatically.

In general, if distortion is not a problem, select the most economical joint. If distortion is a problem, select either a joint in which the weld stresses balance each other or a joint requiring the least amount of weld metal.

Use intermittent welding

Another way to minimize weld metal is to use intermittent rather than continuous welds where possible. For attaching stiffeners to plate, for example, intermittent welds can reduce the weld metal by as much as 75 percent yet provide the needed strength.

Use as few weld passes as possible.

Fewer passes with large electrodes, are preferable to a greater number of passes with small electrodes when transverse distortion could be a problem. Shrinkage caused by each pass tends to be cumulative, thereby increasing total shrinkage when many passes are used.

By creating a heat balance in the material.

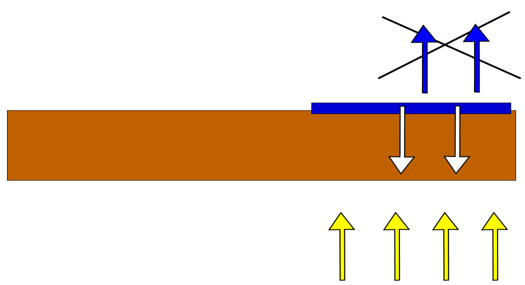


Fig. 14. During the welding process heating can be added in order to create a heat balance from both sides.

Place welds near the neutral axis

Distortion is minimized by providing a smaller leverage for the shrinkage forces to pull the plates out of alignment. Both design of the weldment and welding sequence can be used effectively to control distortion.

Balance welds around the neutral axis

This practice offsets one shrinkage force with another to effectively minimize distortion of the weldment. Here, too, design of the assembly and proper sequence of welding are important factors.

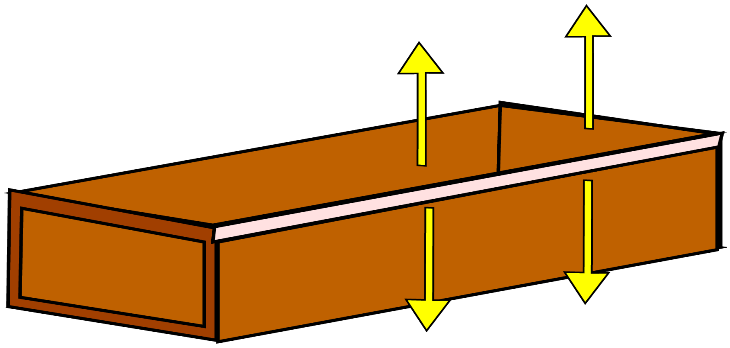


Fig 15. A bad design where the forces will be unsymmetrical, causes a wrong heat balance. The weld is shown in white.

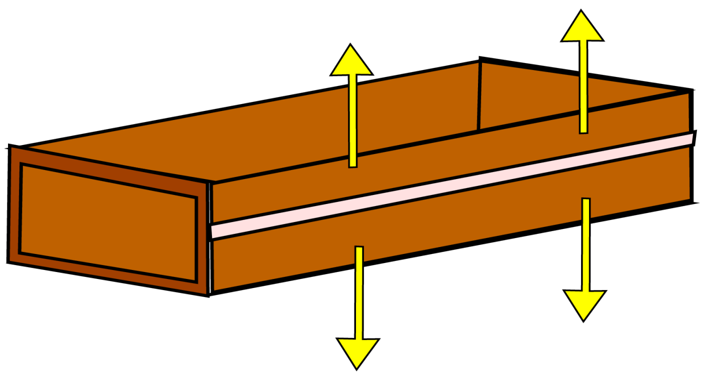


Fig 16. A different design solution giving symmetrical heat balance. The weld is shown in white.

Use backstep welding

In the backstep technique, the general progression of welding may be, say, from left to right, but each bead segment is deposited from right to left As each bead segment is placed, the heated edges expand, which temporarily separates the plates at B. But as the heat moves out across the plate to C, expansion along outer edges CD brings the plates back together. This separation is most pronounced as the first bead is laid. With successive beads, the plates expand less and less because of the restraint of prior welds. Backstepping may not be effective in all applications, and it cannot be used economically in automatic welding.

Anticipate the shrinkage forces

Presetting parts (at first glance, before welding can make shrinkage perform constructive work. Several assemblies, preset in this manner. The required amount of preset for shrinkage to pull the plates into alignment can be determined from a few trial welds.

Pre bending, presetting or pre springing the parts to be welded, is a simple example of the use of opposing mechanical forces to counteract distortion due to welding. The top of the weld groove - which will contain the bulk of the weld metal - is lengthened when the plates are preset. Thus the completed weld is slightly longer than it would be if it had been made on the flat plate. When the clamps are released after welding, the plates return to the flat shape, allowing the weld to relieve its longitudinal shrinkage stresses by shortening to a straight line. The two actions coincide, and the welded plates assume the desired flatness.

Another common practice for balancing shrinkage forces is to position identical weldments back to back, clamping them tightly together. The welds are completed on both assemblies and allowed to cool before the clamps are released. Pre bending can be combined with this method by inserting wedges at suitable positions between the parts before clamping.

Be aware of the heat distortion during assembly and assemble the parts so that you work together with the heat distortion.

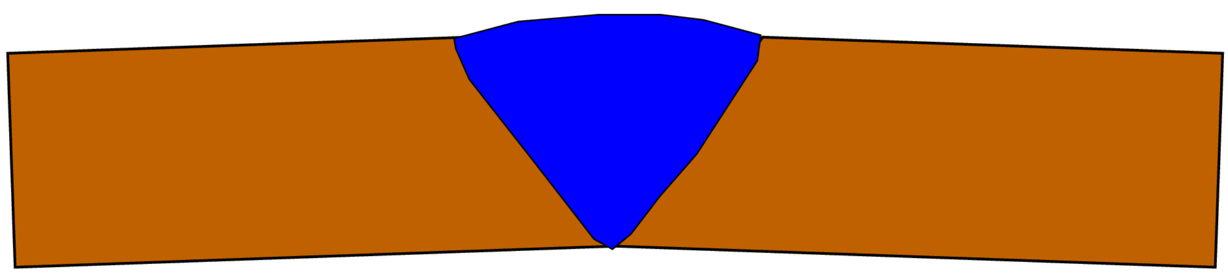


Fig 17. The connection is pre-bent before welding. When the joint has cooled down then the connection will be flat.

Plan the welding sequence

A well-planned welding sequence involves placing weld metal at different points of the assembly so that, as the structure shrinks in one place, it counteracts the shrinkage forces of welds already made. An example of this is welding alternately on both sides of the neutral axis in making a complete joint penetration groove weld in a butt joint. Another example, in a fillet weld, consists of making intermittent welds according to the sequences. In these examples, the shrinkage in weld No. 1 is balanced by the shrinkage in weld No. 2.

Clamps, jigs, and fixtures that lock parts into a desired position and hold them until welding is finished are probably the most widely used means for controlling distortion in small assemblies or components. It was mentioned earlier in this section that the restraining force provided by clamps increases internal stresses in the weldment until the yield point of the weld metal is reached. For typical welds on low-carbon plate, this stress level would approximate 45,000 psi. One might expect this stress to cause considerable movement or distortion after the welded part is removed from the jig or clamps. This does not occur, however, since the strain (unit contraction) from this stress is very low compared to the amount of movement that would occur if no restraint were used during welding.

Minimize welding time.

Since complex cycles of heating and cooling take place during welding, and since time is required for heat transmission, the time factor affects distortion. In general, it is desirable to finish the weld quickly, before a large volume of surrounding metal heats up and expands. The welding process used, type and size of electrode, welding current, and speed of travel, thus, affect the degree of shrinkage and distortion of a weldment. The use of mechanized welding equipment reduces welding time and the amount of metal affected by heat and, consequently, distortion. For example, depositing a given-size weld on thick plate with a process operating at 175 amp, 25 volts, and 75mm/min requires 87,500 joules of energy per linear 25 mm of weld (also known as heat input). A weld with approximately the same size produced with a process operating at 310 amp, 35 volts, and 200mm/min requires 81,400 joules per linear 25mm. The weld made with the higher heat input generally results in a greater amount of distortion.

A Check-list to Minimize Distortion

In summary, follow the check-list below in order to minimize distortion in the design and fabrication of weldments:

- Do not overweld.
- Control fit up.
- Use intermittent welds where possible and consistent with design requirements.
- Use the smallest leg size permissible when fillet welding.
- For groove welds, use joints that will minimize the volume of weld metal. Consider double-sided joints instead of single-sided joints.
- Weld alternately on either side of the joint when possible with multiple-pass welds.
- Use minimal number of weld passes.
- Use low heat input procedures. This generally means high deposition rates and higher travel speeds.
- Use welding positioners to achieve the maximum amount of flat-position welding. The flat position permits the use of large-diameter electrodes and high-deposition-rate welding procedures.
- Balance welds about the neutral axis of the member.
- Distribute the welding heat as evenly as possible through a planned welding sequence and weldment positioning.
- Weld toward the unrestrained part of the member.
- Use clamps, fixtures, and strongbacks to maintain fit up and alignment.

- Pre bend the members or pre-set the joints to let shrinkage pull them back into alignment.
- Sequence sub assemblies and final assemblies so that the welds being made continually balance each other around the neutral axis of the section.
- Following these techniques will help minimize the effects of distortion and residual stresses.

Preheating, interpass and post heating to prevent hydrogen cracking

There are three factors which combine to cause cracking in arc welding:

- hydrogen generated by the welding process
- a hard brittle structure which is susceptible to cracking
- tensile stresses acting on the welded joint

Cracking generally occurs when the temperature has reached normal ambient. In practice, for a given situation (material composition, material thickness, joint type, electrode composition and heat input), the risk of hydrogen cracking is reduced by heating the joint.

Preheat

Preheat, which slows the cooling rate, allows some hydrogen to diffuse away, and prevents a hard, crack-sensitive structure being formed. The recommended levels of preheat for carbon and carbon manganese steel are detailed in EN 1011-2: 2001. The preheat level may be as high as 200°C for example, when welding thick section steels with a high carbon equivalent (CE) value.

Interpass and post heating

As cracking rarely occurs at temperatures above ambient, maintaining the temperature of the weldment during fabrication is equally important. For susceptible steels, it is usually appropriate to maintain the preheat temperature for a given period, typically between 2 to 3 hours, to enable the hydrogen to diffuse away from the weld area. In crack sensitive situations such as welding higher CE steels or under high restraint conditions, the temperature and heating period should be increased, typically 250-300°C for three to four hours.

Post-weld heat treatment (PWHT) may be used immediately on completion of welding, i.e. without allowing the preheat temperature to fall. However, in practice, as inspection can only be carried out at ambient temperature, there is the risk that 'rejectable,' defects will only be found after PWHT. Also, for highly hard enable steels, a second heat treatment may be required to temper the hard micro structure present after the first PWHT.

Under certain conditions, more stringent procedures are needed to avoid cracking. C2 of EN 1011-2. Section C.2.9 of this standard mentions the following conditions:

a. high restraint, including welds in section thickness's above approximately 50mm, and root runs in double bevel joints

b. thick sections ($\geq$ approximately 50mm)

c. low carbon equivalent steels (CMn steels with $C \leq 0.1\%$ and $CE \leq$ approximately 0.42)

d. 'clean' or low sulphur steels ($S \lesssim$ approximately 0.008%), as a low sulphur and low oxygen content will increase the harden ability of a steel.

e. alloyed weld metal where preheat levels to avoid HAZ cracking may be insufficient to protect the weld metal. Low hydrogen processes and consumables should be used. Schemes for predicting the preheat requirements to avoid weld metal cracking generally require the weld metal diffusible hydrogen level and the weld metal tensile strength as input.