UNIVERSITY OF THESSALY
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

METHODS TO CONTROL DISTORTIONS OF WELDED STRUCTURES

by
DAOUTIS GEORGIOS
Mechanical Engineer, University of Thessaly, 2023

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at the University of Thessaly

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Abstract

Welding can be accomplished using various methods, including gas, arc, resistance and laser welding, among others, for industrial use, from construction and manufacturing to transportation and aerospace. Welding process which is used in constructing for big and complicated constructions gives many assets from other mechanical joining technics such as better structural ability, weight and budget savings, options in designing. Unfortunately residual stresses occur in welding construction and inevitably end into distortion.

Welding distortion is a common problem that can occur in various types of welded structures that can compromise their strength and performance. An overview of the types of welding distortions that can occur, is presented, including angular distortion, longitudinal distortion, transverse distortion, and distortion due to welding shrinkage. The physical principles underlying each type of distortion are mentioned, including the factors that influence their magnitude and direction.

It is also presented methods for predicting, measuring each type of distortion, including welding process parameters, mechanical and thermal methods, and design optimization. The advantages and limitations of each method are also presented and also a comprehensive overview of the types of welding distortions that can occur, as well as methods for predicting and mitigating them.

Welding distortions occur because of the expansion and contraction of the weld material during the welding process. The welding parameters contribute a significant effect on the magnitude and distribution of the welding which lead into distortion. In summary, the welding parameters can have a significant effect on welding distortions. It is crucial to carefully control and optimize these parameters to minimize the magnitude and distribution of welding distortions. However, there are several methods that can be used to control welding distortion prior to welding. Some of these methods are: welding sequence, backstep welding, preheating, fixturing, joint design, welding parameters, backing material, use of clamps and jigs, use of tack welds. Overall, a combination of these methods can be used to minimize the distortion by using them before welding.

Apart from controlling distortion before welding, method to minimize distortion after welding exist such as post-weld heat treatment. Post-weld heat treatment can help to reduce

residual stresses and minimize distortion. This technique is about warming up the welded material to a temperature and then cooling down at a slow pace.

On conclusion controlling distortion in welded structures requires careful planning, proper fixturing and an understanding of the welding procedure and how the material is being effected since durability and strength of a welding is the key factor to a sustainable structure.

ΜΕΘΟΔΟΙ ΕΛΕΓΧΟΥ ΠΑΡΑΜΟΡΦΩΣΕΩΝ ΣΥΓΚΟΛΛΗΣΕΩΝ

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Περίληψη

Η συγκόλληση μπορεί να πραγματοποιηθεί χρησιμοποιώντας διάφορες μεθόδους, όπως συγκόλληση αερίου, τόξου, αντίστασης και λέιζερ και χρησιμοποιείται σε ένα ευρύ φάσμα κατασκευών έως και την αεροδιαστημική. Η εφαρμογή των διαδικασιών συγκόλλησης στην κατασκευή μεγάλων και πολύπλοκων κατασκευών παρέχει πολλά πλεονεκτήματα σε σχέση με τις μεθόδους μηχανικής σύνδεσης, όπως βελτιωμένη δομική απόδοση, εξοικονόμηση βάρους και κόστους, ευελιξία σχεδιασμού. Ωστόσο, η συγκόλληση προκαλεί παραμένουσες τάσεις που οδηγούν σε παραμόρφωση.

Η παραμόρφωση λόγω συγκόλλησης είναι ένα κοινό πρόβλημα που μπορεί να εμφανιστεί σε διάφορους τύπους συγκολλητών κατασκευών που μπορεί να θέσει σε κίνδυνο την αντοχή και την απόδοσή τους. Παρουσιάζεται μια επισκόπηση των τύπων παραμορφώσεων συγκόλλησης που μπορούν να συμβούν, συμπεριλαμβανομένης της γωνιακής παραμόρφωσης, της διαμήκους παραμόρφωσης, της εγκάρσιας παραμόρφωσης και της παραμόρφωσης λόγω συρρίκνωσης. Αναφέρονται οι φυσικές αρχές που διέπουν κάθε τύπο παραμόρφωσης, συμπεριλαμβανομένων των παραγόντων που επηρεάζουν το μέγεθος και την κατεύθυνσή τους.

Παρουσιάζονται επίσης μέθοδοι για την πρόβλεψη, την μέτρηση και την ελαχιστοποίηση κάθε τύπου παραμόρφωσης, συμπεριλαμβανομένων των παραμέτρων της διαδικασίας συγκόλλησης, των μηχανικών και θερμικών μεθόδων και της βελτιστοποίησης του σχεδιασμού. Παρουσιάζονται επίσης τα πλεονεκτήματα και οι περιορισμοί κάθε μεθόδου και επίσης μια περιεκτική επισκόπηση των τύπων παραμορφώσεων συγκόλλησης που μπορεί να προκύψουν, καθώς και μέθοδοι πρόβλεψης και μετριασμού τους.

Οι παραμορφώσεις συγκόλλησης συμβαίνουν λόγω της θερμικής διαστολής και συστολής του υλικού συγκόλλησης κατά τη διάρκεια της διαδικασίας συγκόλλησης. Οι παράμετροι συγκόλλησης μπορούν να έχουν σημαντική επίδραση στο μέγεθος και την κατανομή αυτών των παραμορφώσεων. Είναι σημαντικό να ελέγχεται προσεκτικά και να βελτιστοποιούνται αυτές οι παράμετροι για να ελαχιστοποιήσετε το μέγεθος και την κατανομή των παραμορφώσεων συγκόλλησης. Ωστόσο, υπάρχουν διάφορες μέθοδοι που μπορούν να χρησιμοποιηθούν για τον έλεγχο της παραμόρφωσης της συγκόλλησης πριν από τη συγκόλληση όπως η αλληλουχία συγκόλλησης, η προθέρμανση, οι παράμετροι συγκόλλησης, η χρήση σφιγκτήρων. Συνολικά, ένας συνδυασμός αυτών των μεθόδων μπορεί να χρησιμοποιηθεί για τον έλεγχο της παραμόρφωσης συγκόλλησης πριν από τη συγκόλληση.

Εκτός από τον έλεγχο της παραμόρφωσης συγκόλλησης πριν από τη συγκόλληση, υπάρχουν μέθοδοι για την ελαχιστοποίηση της παραμόρφωσης μετά τη συγκόλληση, όπως η θερμική επεξεργασία μετά τη συγκόλληση. Η θερμική επεξεργασία μετά τη συγκόλληση μπορεί να βοηθήσει στην μείωση ή την εξάλειψη των υπολειπόμενων τάσεων και στην ελαχιστοποίηση της παραμόρφωσης. Αυτή η τεχνική περιλαμβάνει τη θέρμανση του υλικού σε μια συγκεκριμένη θερμοκρασία και στη συνέχεια την ψύξη του.

Συμπερασματικά, ο έλεγχος της παραμόρφωσης σε συγκολλητές κατασκευές απαιτεί προσεκτικό σχεδιασμό, σωστή στερέωση και κατανόηση της διαδικασίας συγκόλλησης και των επιπτώσεών της στο υλικό, καθώς η ανθεκτικότητα και η αντοχή μιας συγκόλλησης είναι ο βασικός παράγοντας για μια βιώσιμη κατασκευή.

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1 Introduction

Welding is a common manufacturing process used to join two or more metal parts or even parts of other material together permanently with an advancing pace of use due to better structural ability, weight and budget savings, options in designing. While it is a reliable method, welding can cause unavoidable distortions in the shape and dimensions of the welded parts. Welding distortions are caused by high temperatures which appear during the welding process, which cause localized expansion and contraction of the metal. These distortions can lead to problems such as misalignments, changes in geometry, and structural defects, which can compromise the quality and functionality of the welded product. Therefore, understanding and controlling welding distortions is crucial for ensuring the reliability and safety of welded structures. In this context, this topic has gained considerable attention in the field of welding engineering, and a range of methods have been developed to mitigate the effects of welding distortions.

The usage of welding, a typical production technique for permanently joining two or more metal pieces together, is increasing due to improvements in structural strength, weight and cost reductions, and design flexibility. Welding can result in unavoidable distortions in the shape and size of the welded parts, despite the fact that it is a dependable process. High temperatures that develop during the welding process, which lead to localized metal expansion and contraction, are the root cause of welding deformities. These distortions may result in issues with the welded product's quality and functionality, including misalignments, geometry alterations, and structural flaws. Therefore, it is essential to comprehend and manage welding distortions in order to guarantee the dependability and safety of welded constructions. Residual stresses are occurring due to preventing the free shrinkage of weld and base material around it. Residual stresses and distortions can occur near the joint due to localized welding process and subsequent rapid cooling. They affect the fatigue behavior during external loading significantly. This effect of residual stresses may be beneficial or detrimental, depending upon the sign, magnitude and their distribution. Generally tensile residual stresses are detrimental and will reduce the fatigue life of the structure as they increase the fatigue crack growth rate and decrease the threshold value of stress intensity factor, while fatigue strength can be increased by compressive residual stresses and they reduce the crack growth rate.

1.1 Scope and outline of thesis

The scope is to point out in what degree the welding process is affected and specifically in which factors such as strength of the joints. The objective is to find out, what type of residual stresses will be appeared on the weld. The next chapter gives a theoretical background of the topic. Chapter 3 gives the description for indicative cases of distortion on different kinds. Effect of welding parameters is presented on the following chapter. The next part presents methods to prevent distortion before welding and the final chapter is referred in methods to reduce distortion after welding which means post welding treatment. The final chapter is a conclusion section.

1.2 Summary of Introduction

Problems that arise into the fabrication industry regarding distortion control and prediction have been pointed out. The theoretical knowledge, experimental data and financial data provides us earlier knowledge of distortion in the development and design process has significant benefits in constructing large and complex items into mass production without strength or economics issues. At the first stages in design any modifications in welding procedures are more cost effective, as it is well known and unfortunately proved that that the cost of repairing climbs dramatically though the duration of a product development, and increases significantly once the manufacturing phases start. Unfortunately distortion in welding is discovered when it cannot be redesigned, and so changes have to be made on the final product. Modifications and repairs add costs. Early knowledge is the main factor in avoiding time and cost problems.

2 How are distortions generated during welding

2.1 Introduction in welding

Welding is about a process that has to do with joining two or more pieces of metal through heating, melting, and cooling, usually with the use of a filler material. The process creates a strong, permanent bond between the materials, allowing them to function as a single unit. Welding can be accomplished using various methods, including gas, arc, resistance, and laser welding, among others, and is commonly used in fabrication, from construction and manufacturing to transportation and aerospace. Welding processes in fabricating large and complex structures provides several advantages over mechanical joining methods such as improved structural performance, weight and cost savings, flexibility of design. However, welding induces residual stresses which result into distortion. Welding distortion in structures fabricated cause reduction of structural integrity, dimension problems and increased fabrication costs.

2.2 Causes of welding distortions

Expanding and contracting of heated and cooled material, non-uniform stresses are formed (Fig.2.1). Distortions can be generated during welding due to a variety of factors, including:

2.2.1 Thermal Expansion

On heating a metal, normally it expands. During welding, the metal being welded gets heated up to its melting point, which causes it to expand. This expansion can create distortions in the weldment, especially if the weld is long and thin. Thermal expansion is a natural property of most materials, including metals. When metals are heated, they expand, and when they cool down, they contract. In welding, the high temperatures involved can cause significant thermal expansion and contraction, which can affect the final size and shape of the welded joint.

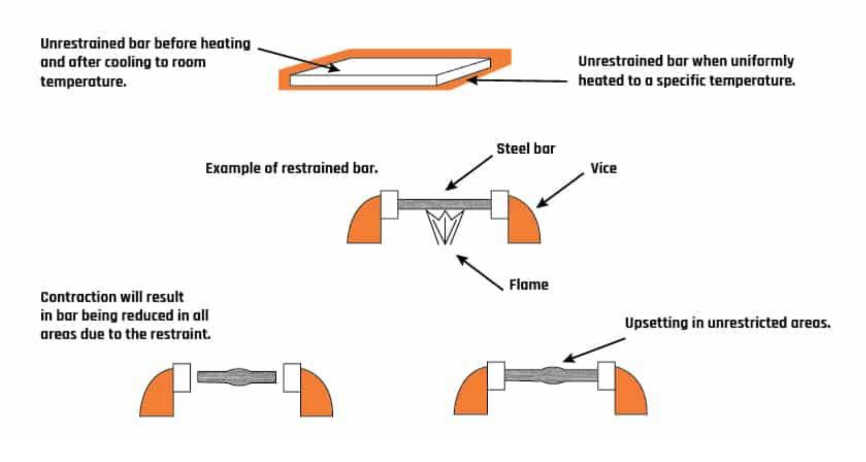


Figure 2.2 Shrinkage and contraction in welding [1]

When a metal is heated during welding, it expands in all directions. If the metal is restrained, such as in a welded joint, the expansion will create internal stresses within the material. As the metal cools and contracts, these stresses can cause distortion, warping, or even cracking in the welded joint.

To minimize the effects of thermal expansion in welding, several techniques can be used. Controlling the effects of thermal expansion in welding is crucial to reassure the high level and integrity of the welding. Welders should be aware of the potential for thermal expansion and contraction and take appropriate measures to minimize its impact on the final product.

2.2.2 Shrinkage

When the weld cools down, it contracts. This contraction can cause the weldment to distort. Shrinkage in welding is a phenomenon that occurs when a welded joint cools down after being heated during the welding process. As the joint cools, it contracts, which can cause the metal around the joint to deform or distort. This deformation is known as shrinkage.

Shrinkage is particularly common in materials like steel, which have a high thermal expansion coefficient. When steel is warmed up during welding, it expands, and contracts when it cools. If the weld is not properly designed or executed, this contraction can cause the metal to pull in different directions, which can result in stress, cracking, or distortion of the weld. Ultimately, the key to preventing shrinkage is to design the weld joint with shrinkage in mind and to use welding techniques that are appropriate for the materials and conditions involved. This can help ensure that the finished weld is strong, durable, and free from defects.

2.2.3 Uneven heating

If the heat input into the metal is not even, then different parts of the metal will expand and contract at different rates, which can lead to distortions. Uneven heating in welding can lead to a number of problems, including distortion, cracking, and weakening of the weld. It is important to achieve even heating in welding to reassure a strong and durable weld.

Some common causes of uneven heating during welding include:

- Uneven distribution of heat input: This can occur when the welding operator moves too quickly or too slowly across the joint, resulting in some areas receiving more heat input than others.
- Inconsistent travel speed: If the travel speed is inconsistent during the welding process, some areas of the joint may receive more heat input than others.
- Uneven preheating: If the preheating of the joint is not done evenly, it can lead to uneven heating during the welding process.
- Inadequate joint preparation: If the joint is not properly prepared before welding, it can result in uneven heating.
- Improper fit-up: If the metal parts being welded are not properly aligned or fit together, the welding process can create distortions.
- Welding speed: If the welding speed is too slow, the metal can be heated for too long, which can cause it to expand and create distortions.

- Fixturing: If the metal being welded is not properly held in place during welding, it can move or shift, which can cause distortions.

2.3 Heat transfer in welding

Heat transfer during the welding process is generated by an external heat source, such as an electric arc, a laser beam, or a gas flame. This heat is used to fuse, melt, metal pieces (Fig. 2.2). The transfer of heat in welding is governed by many factors, such as the type of welding process used, welding parameters, material properties of the metals being welded, the environment in which the welding takes place. The most common types of transferring the heat in welding are conduction, convection, and radiation.

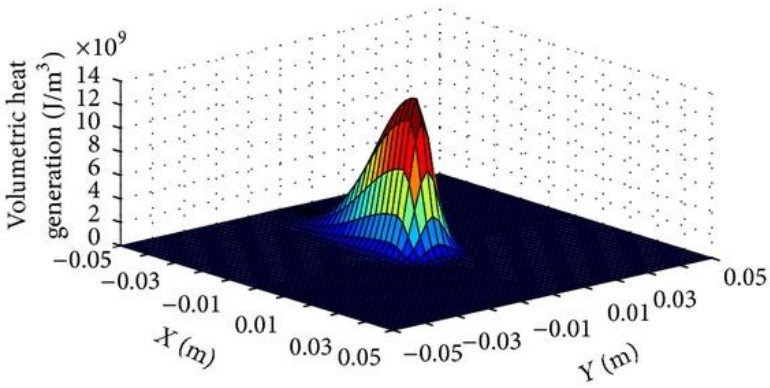


Figure 2.2 Temperature Distribution in Submerged Arc Welding [2]

Conduction is transferring the heat of energy through a material by means of molecular motion. In welding, conduction occurs when the heat source heats the base metal, which then transfers heat to the adjacent metal. The rate of conduction is influenced by metal’s thermal conductivity, which varies depending on the material.

Convection is the heat transfer of energy through the movement of a fluid, such as air or a gas. In welding, convection occurs when the heat generated by the welding process heats the surrounding air or gas, which then transfers heat to the metal being welded. The rate of convection is influenced by factors like the welding parameters, gas, air flow rate and shape, size of the weld.

Radiation is the transfer of heat energy through electromagnetic waves. In welding, radiation occurs when the welding process is heated by electromagnetic radiation, such as visible light or infrared radiation. The rate of radiation is influenced by factors such as the welding process that is used and its parameters. Overall, understanding heat transfer in welding is important for ensuring the quality and integrity of the welded joint. Proper control of heat transfer can help prevent defects such as porosity, cracking, and distortion, which can compromise the strength and reliability of the welded joint. A first introduction to welding mechanics is given, based at this stage on uncoupled analytical solutions for thermal and thermomechanical behavior. Rosenthal’s well-known quasi-static solution for the field of temperature caused by a fast-moving, concentrated source of heat is used to demonstrate the affection of material properties and welding conditions over the temperature fields (Fig. 2.3). An approximate thermo-mechanical solution due to Okerblom [2] is used to demonstrate the roles of the thermal dilatation of the material being welded and the heat input on welding deformations. This solution is also used to mention the development of residual stress fields and probable buckling distortion.

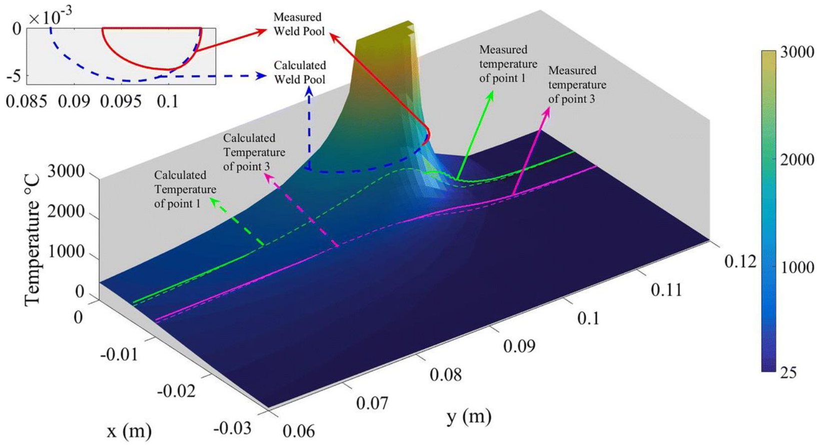


Figure 2.3 Temperature distribution of the 316L stainless steel plate by using Rosenthal's equation [2]

2.4 Heat transfer in welding procedure

The main issue on weldings is the thermal field which affects many factors during the procedure of welding. High temperature develops near the welding area and away from them temperatures still stay in low fields. Also, the heat source that welds is a moving factor, therefore the thermal field is not constant but a variation of time and space. This thermal field affects the mechanic and the metallurgical properties of the welding such as the structure and base metal width, the structure and the range of Heat Affected Zone (HAZ) and the residual stresses and distortions that appear on the welding structure. All the above are critical factors for the strength, the quality and the engineering properties of the structures that are welded. So, the significance for the engineer is to understand the thermal field on a welding and the contribution of the welding parameters that being applied.

At first the energy that is given to an arc welding with voltage V and current I is P=VI but the thermal power that is useful for the welding procedure is a factor depending on the kind of the welding procedure. The welding processes defined by standards are categorized and along with the performance in each process they ate summarized as shown on the table below (Table 2.1).

Table 2.1 performance levels for different welding processes [3]

Welding procedure	Performance level
SMAW	0,7-0,9
GMAW(MIG-MAG)	0,7-0,9
GTAW	0,6-0,8
SAW	0,8-0,95
LBW	0,05
EBW	0,8-0,95

SMAW stands for Shielded Metal Arc Welding. It is about a process where an electric arc is formed between a coated electrode and the base metal to be welded. The coating on the electrode melts and this creates a protective gas shield on the weld, preventing oxidation and contamination of the weld.

SMAW is a widely used welding process in industries such as construction, shipbuilding, and pipeline fabrication, as it is a versatile and relatively easy-to-learn process. It is widely used, including carbon steel, stainless steel, and cast iron materials. However, typically is slower than other welding processes, and the electrodes need to be changed frequently, which can be time-consuming.

GMAW stands for Gas Metal Arc Welding, which is commonly used for industrial settings. It uses a wire electrode that is fed through and an inert shielding gas, to prevent atmospheric contamination from the weld. The electric arc is created between the wire and the item to be welded, melting both wire and metal and fusing both. GMAW is known for its versatility, high productivity, and ability to produce high-quality welds in a large scale of materials, such as and aluminum.

GTAW stands for Gas Tungsten Arc Welding, is a process that uses a tungsten electrode to execute the weld. The welding is protected from air contamination with an inert shielding gas, usually argon or a mixture of argon and helium. The tungsten electrode creates an electric arc with the material to be welded, melting both the tungsten and the material, but not the electrode itself. A filler metal may be added separately, if necessary. GTAW is known for its high quality and precision, making it a popular choice for welding thin materials, such as aluminum, magnesium, and stainless steel, as well as for critical constructions, like aviation and nuclear plants.

Submerged Arc Welding (SAW) is a welding process that uses a wire electrode, a granular flux to shield the welding area. The arc is created among the wire and the material, melting them and fusing both. The flux melts and solidifies to forma slag that covers the weld, protecting it from oxidation and allowing it to cool more slowly, which can help prevent cracking. SAW is known for its high deposition rates and suitability for welding thick materials, making it a popular choice for heavy fabrication work, such as shipbuilding, pressure vessel manufacturing, and pipeline construction.

Laser beam welding (LBW), which uses as the heat source a laser beam to join two parts of objects. LBW is usually performed additionally or not of an intermediate material, depending on the application. The laser beam provides a concentrated heat source, which allows for precise check of the applied heat on the item to be welded. LBW is commonly used in constructions with small tolerances and high accuracy.

EBW stands for Electron Beam Welding, which uses a beam of high-velocity electrons to perform the welding between the metal parts. The electrons have high speeds and focused on a narrow beam using an electron gun. The beam is directed at the workpiece, which is typically placed in a vacuum chamber to prevent atmospheric contamination. When the beam strikes the workpiece, it generates heat, which melts the metal and fuses the two pieces together. EBW is known for its ability to produce high-quality welds with minimal distortion, making it a popular choice for extremely high precision weldings, such as in the aerospace, automotive, and semiconductor industries.

To summarize in few words the connection between the above welding processes and the performance levels can be described totally by the following;

SMAW, GMAW have high performance level due to metal drops from the electrode or the welding wire.

GTAW has high performance level.

SAW extremely high performance due to the fact that practically the arc welding is insulated.

LBW low performance by high reflection on the surface.

EBW absorbs almost the full energy.

Apart from all the above, the welding speed u is critical a significant factor and the total contribution of the process of a welding and the heat input (h) is given by the following equation:

h=nVI/u

where voltage V, current I, welding speed u and n the coefficient of performance.

The basic principle of solving this heat transfer matter is that only through conduction heat transfer takes place and the equation is x [1]

$$\rho c \frac{\partial T}{\partial t} = Q' g + \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k \frac{\partial T}{\partial z}) \quad 2.1$$

Where ρis density of the material (kg/m^3)

C specific heat (J/kgK)

k thermal conductivity(W/mK)

Q’g heat production rate through internal sources (W/m^2)

After modifications and acceptances which are:

Q’g=0 (no gain or loss of heat inside the material)

$\frac{\partial k}{\partial T} = 0$ (k is not depended on temperature T)

α=k/ρc thermo-diffusion of the material (m^2/s)

We also accept that the procedure of the welding is a three-phase time problem including start, move and stop of the welding arch(Fig. 2.4) and if we adopt that the axis system Oxyz is moving we have quasi stationary state and the axis system transforms from Oxyz to Oxyw where variable w=x-ut

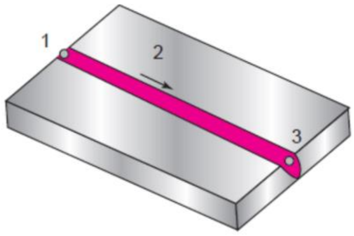


Figure 2.4 3-phase in welding procedure1 start 2 move 3 stop [3]

We end in $\frac{\partial^2 T}{\partial w^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=-\frac{u}{a}(\frac{\partial T}{\partial w})$ 2.2

and the solutions of the above exercise are given by Rosenthal and regard temperature distributions on weldings.

2.5 Temperature distributions

Three simple case studies are:

i. welding on an extremely thick plate where the thermal source is considered to be a point (Fig. 2.5) and temperature distribution is

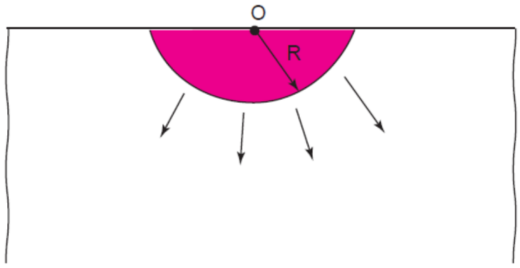


Figure 2.5 thermal source is considered to be a point [3]

Plate thickness H→∞, R→∞

$R=\sqrt{w^2+y^2+z^2}$

$\frac{\partial T}{\partial z}=0$

z=0

Considering $T=T_o$ the initial temperature of the plate and R→∞ we have the expression for temperature distribution

$$T-To=\frac{Q}{2\pi k}e^{-\frac{u}{2a}w}\frac{e^{-\frac{u}{2a}R}}{R}\quad (2.3)$$

of a thick plate where the thermal source is considered to be a point

ii. Welding of a certain thickness plate and the source of heat considered to be a point (Fig. 2.6)

$$\frac{\partial T}{\partial z} = 0$$

z=0 and z=H

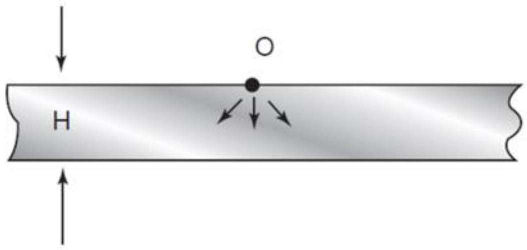


Figure 2.6 the source of heat considered to be a point on a certain thickness plate [3]

$$T - To = \frac{Q}{2\pi k} e^{-\frac{u}{2a}w} \left[\frac{e^{-\frac{u}{2a}R}}{R} + \sum_{n=1}^{\infty} \left(\frac{e^{-\frac{u}{2a}R_n}}{R_n} + \frac{e^{-\frac{u}{2a}R_n^{'}}}{R_n^{'}} \right) \right] \quad (2.4)$$

Where $R_n = \sqrt{w^2 + y^2 + (2nH - z)^2}$

$R_n^{'} = \sqrt{w^2 + y^2 + (2nH + z)^2}$

iii. Thin plate with indefinite width(Fig. 2.7)

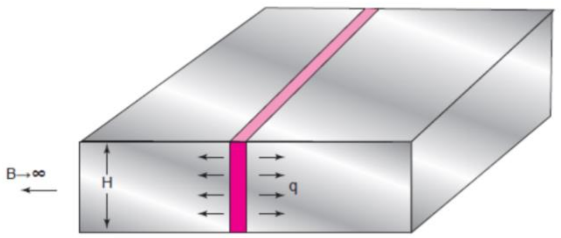


Figure 2.7 Thin plate with indefinite width [3]

Heating source q=Q/H

$$T - To = \frac{q}{2\pi k} e^{-\frac{u}{2a}w} K_o\left(\frac{u}{2a} r\right) \quad (2.5)$$

With

$r = \sqrt{w^2 + y^2}$ and Ko(n) a modified Bessel function

Welding speed affection on temperature on plate with indefinite width and base metal affection on plate with indefinite width are also two significant parameters on temperature on the welding.

2.6 Cooling rate and maximum temperature

It is significant to calculate the cooling rate on a welding due to the fact that knowing the temperature could prevent metallurgical changes in microstructure such as martensite transformation in steels.

The cooling rate is

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial w}\frac{\partial w}{\partial t}$$
$$\frac{\partial w}{\partial t} = -u \qquad (2.6)$$
$$\frac{\partial T}{\partial t} = -u\,\frac{\partial T}{\partial w}$$

So, we conclude into the Adams solutions on the welding axis (y=0 and z=0) and for thick plates we have

$$\frac{\partial T}{\partial t} = 2\pi k\,\frac{(T - T_o)^2}{h} \quad (2.7)$$

And for thin plates

$$\frac{\partial T}{\partial t} = 2\pi k \rho c \left(\frac{H}{h}\right)^2 (T - T_o)^3 \quad (2.8)$$

Where h=nVI/u

The decision of using the above equations comes through the calculation of the relative thickness of the plate H_o

$$H_o = H\sqrt{\frac{\rho c (T - T_o)}{h}} \quad (2.9)$$

If H_o>0,75 thick plate equation is used otherwise we use the other equation.

2.7 A second approach of the factors on the heating and the cooling rate on weldings by Okerblom

2.7.1 Introduction

Metallic structures usually are joined permanently with welding. Unfortunately, residual stresses and deformations occur sometimes and unavoidably this leads into big fabrication issues, mainly in time and additional cost. Thin plate and shell structures are two categories of welding constructions that are affected in a large scale.

Distortion and residual stress comes as a result of expanding and contracting during the passage of the source of heat. In structures were angular deformation appears on the line of weld, such as in Fig. 2.8 longitudinal contraction forces, which give rise to bending and may indeed cause buckling. The magnitude of these effects depends on the amount of the thermal energy input on the welding. Reductions in distortion cannot be avoided without changing the heat input and this may risk other defects on the integrity of the weld.[2]

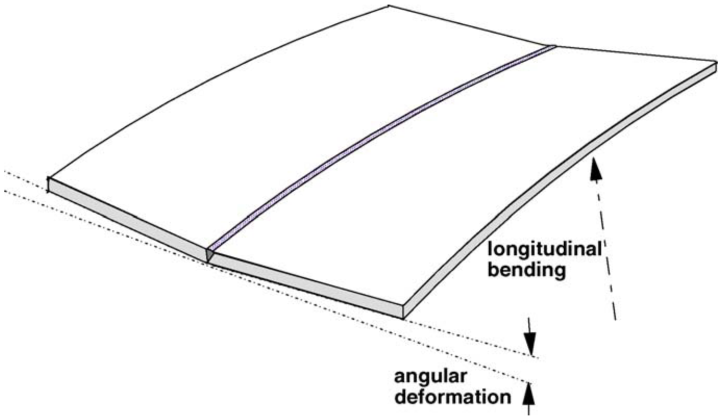


Figure 2.8 Typical welding distortions [4]

As a first step towards simplification, the sequential, thermal transient and thermo-elastic–plastic stages of the computation may be uncoupled without penalty. The transient temperature field calculated in the first stage then provides input to the thermo-elastic–plastic stage.

The outputs of this stage, in the form of transverse angular deformation and contraction forces, gives the final deformations in the structure.

Several researchers show that the transient temperature fields can be computed adequately using finite-element methods, given some experimental support from generic welding trials. The final elastic deformations of the structure, due to the accumulation of individual welds, can also be computed relatively easily, provided that results from a thermo-elastic–plastic stage are available.

The challenge is to present simplified the elastic–plastic stage of the process, starting from a transient temperature field input and leading to outputs of angular deformation and a contraction stress field.

2.7.2 Simplified analytical model

These approaches that are presented below were based on the early ideas of Okerblom who tried to simplify analytical models in order to predict deformations and specifically angular that appear by contraction on the longitudinal axis.

Okerblom was the first to draw attention to these features and argued that the thermomechanical processes might therefore be modelled by considering a transverse plane strain slice, which would be passed through the quasi-stationary temperature field in the direction of welding.

In the case of the angular deformation the final formulation given in reference expresses the transverse angular deformation θ in terms of the relative depth of penetration of the weld s/t and the relative width of the fusion zone on the surface b/t as [5]:

$$\theta = \frac{s}{t}\frac{b}{t} a T_s \left[3\left(1-k^2\right) - 2\frac{s}{t}\left(1-k^3\right) \right] \quad (2.9)$$

where k is a geometric parameter dependent on the shape of the fusion zone (parallel, triangular or parabolic). The specific heat input rate does not figure in this formulation, as suggested earlier, but note that the transverse mean contraction of the weld depends on the volume of the fusion zone and therefore on the specific heat input rate.

In the case of the longitudinal stress (MTS) algorithm, the thermal strain mismatches develop longitudinal contraction forces during the cooling phase and these spread progressively outwards as the plane strain slice passes through the transient temperature field. An important consequence of this is that the development of longitudinal stress is driven mainly by the envelope of maximum temperatures reached across the slice (Fig. 2.9).

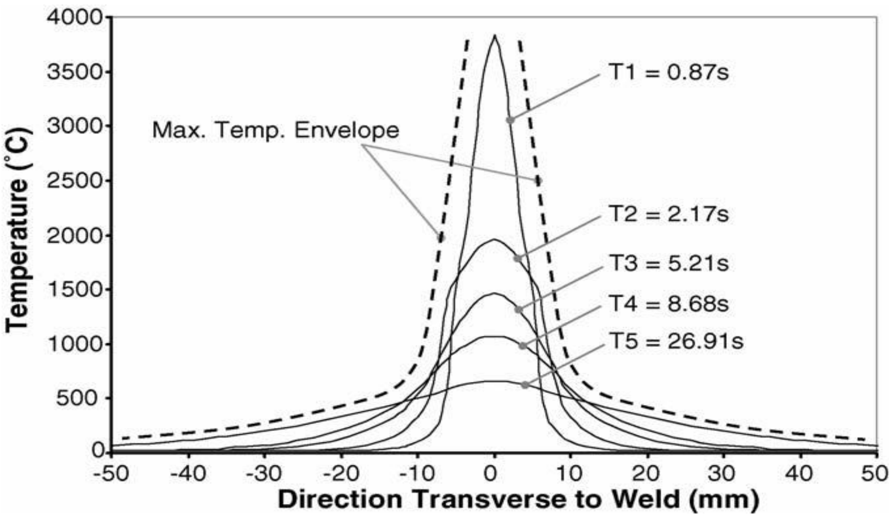


Figure 2.9 Envelope of maximum temperature plots reached across a transverse slice of the plate at different times following welding. [5]

Although these temperatures are attained at various times in practice, there are always mismatches at each transverse site, therefore it is assumed that the time offset is not necessary in achieving the corresponding maximum.

However, unlike the shrinkage volume approach, the contraction forces in this approach are governed by the entire temperature field rather than the behavior of a designated region. Because of the intricacies of material behavior discussed previously, the longitudinal stress element is the most difficult to analyze in concept.

2.8 How does distortion occur

Welding is about a process of joining two or more pieces of materials by heating the surfaces to their melting points and applying pressure to fuse them together. When a weld is laid it is molten metal and therefore hot, as it cools it shrinks, this shrinkage generates stress on the weld and the base material near the weld. Distortion normally is created by localized heating of the base metals which normally creates expansion and contraction on the operation of the weld. The restricted movement by the expansion and contraction has a result of these residual stress to appear.

Distortion that is caused by residual stresses usually appear because of the different temperature states on the welding procedure such as heat rise, heat peak and cooling down sequence on the weld but also on the heat affected zone. This dynamic procedure is changing constantly. On heating at first, compressive residual stress appears on the area of base metal which is being heated for melting due to thermal expansion and the same (thermal expansion) is restricted by the small temperature around the base metal. On the highest value of temperature compressive residual stress gradually decreases due to softening of metal being heated.

The procedure that was described reduces to zero value stress when melting starts and a reverse situation starts on the welding. During cooling as metal starts to shrink, tensile residual stresses develop and the stress magnitude keeps on increasing until room temperature of the metal.

This heat is what it makes expansive and contractive phenomena. When heating and cooling is uneven, distortion may appear. On welding we have to deal with concentrated heating source which will lead to fuse the material but also will create due to the expansion and contraction of the heated material residual stresses. Therefore, compressive and tensile stresses are created on the cold base metal when the weld pool is formed due to the thermal expansion of the hot metal (heat affected zone) and respectively tensile stresses appear on dropping the temperature when the contraction of the weld and the immediate heat affected zone is resisted by the bulk of the cold base metal (fig 2.10). Limited skills or lack of practice and preparation, or being careless could be the reason for defects on welds. Whatever the reason is, these could lead into cost in money or time which are both critical for fabrication because weld defects such as weld distortion is the reason and the unwanted result.

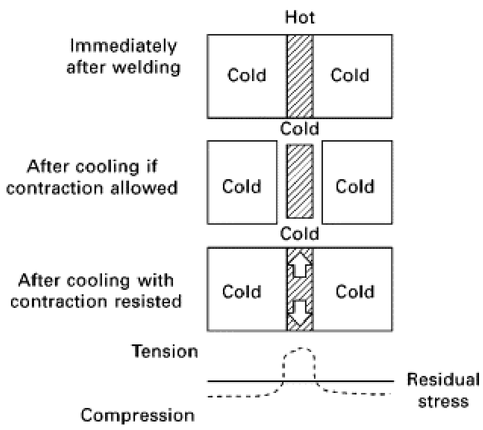


Figure 2.10 Formation of residual stresses due to welding [6]

The volume change in the weld region during solidification and subsequent cooling to room temperature reveals the degree of thermal stresses introduced into the material. When welding CMn steel, for example, the molten weld metal volume is reduced by roughly 3% upon solidification, and the volume of the solidified weld metal/heat affected zone (HAZ) is reduced by an additional 7% when its temperature lowers from the melting point of steel to room temperature.

When the yield strength of the material is exceeded by the stresses that are generated by expansion or contraction, plastic deformation takes place of the material. A permanent reduction is caused by plastic deformation, in the component dimensions and affects the structural integrity.

2.9 Weld Distortion

Weld distortion refers to the changes in the shape and dimensions of a welded joint that occur as a result of the welding process. Welders and even those with great experience commonly struggle with the problem of weld distortion. Distortion is a main issue for many reasons, but one of the most critical is the structural integrity of the construction.

2.10 What is weld distortion

Weld distortion is caused by the expansion and contraction of the weld metal and nearby base metal throughout the welding process's heating and cooling cycles. When all of the welding is done on one side of a part, the distortion is substantially greater than when the welds are alternated from one side to the other. Many elements, such as physical and mechanical qualities that vary as heat is applied, affect metal shrinkage and cause deformation during this heating and cooling cycle. For example [7], as the temperature of the weld area rises, the steel plate's yield strength, elasticity, and thermal conductivity drop, while thermal expansion and specific heat rise (Fig. 2.11). These changes, in turn, alter heat flow and heat distribution homogeneity.

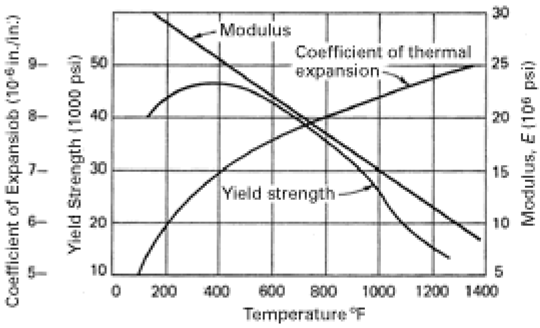


Figure 2.11 Changes in steel characteristics as temperature rises hinder study of what happens throughout the welding cycle - and hence comprehension of the elements contributing to weldment deformation. [7]

2.11 Reasons for distortion

Consider the steel bar depicted in Fig. 2.12 to learn how and why deformation develops during heating and cooling of a metal. The bar grows in all directions when it is uniformly heated, as seen in Fig. 2.12(a). The metal compresses uniformly to its original size as it cools to ambient temperature.

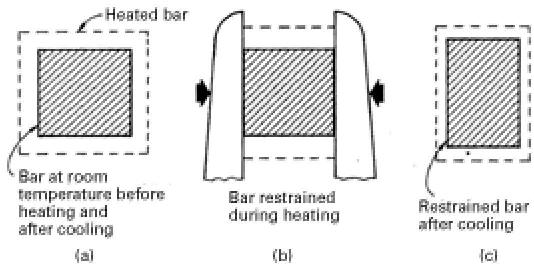


Figure 2.12 If a steel bar is uniformly heated while unrestrained, as in (a), it will expand in all directions and return to its original dimensions on cooling. If restrained, as in (b), during heating, it can expand only in the vertical direction - become thicker. [7]

However, lateral expansion cannot occur if the steel bar is held - as in a vise - while heated, as shown in Fig. 2.12(b). However, because volume expansion must occur during heating, the bar extends vertically (in thickness) and becomes thicker. As the deformed bar cools, it will still tend to contract equally in all directions, as seen in Fig. 2.12(c). The bar is now thinner but shorter. It has been warped or distorted indefinitely (To simplify, the illustrations depict this distortion occurring just in thickness. However, length is similarly influenced.)

In a welded junction, the same expansion and contraction forces act on the weld metal and the base metal. As the weld metal solidifies and unites with the base metal, it reaches its maximum length. When chilled, it tries to compress to the volume it would normally occupy at the lower temperature, but is prevented from doing so by the nearby base metal. As a result, tensions arise between the weld and the adjacent base metal.

As a conclusion from all the above we end in distortions which are categorized in the following chapter in with many types.

3 Types of welding distortions

3.1 Introduction

Welding distortions of many forms can develop during the welding process. These include:

- Longitudinal distortion: This sort of distortion occurs along the weld's length and is caused by the weld metal shrinking as it cools. This can result in the welded parts becoming longer or shorter than they were before welding.

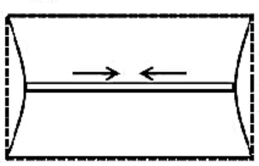


Figure 3.1 longitudinal shrinkage [4]

- Transverse distortion: Transverse distortion occurs across the thickness of the weld, and is caused by the weld metal shrinking in a perpendicular direction to the length of the weld. This can result in the welded parts becoming wider or narrower than they were before welding.

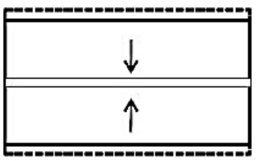


Figure 3.2 Transverse shrinkage [4]

- Angular distortion: Angular distortion occurs when the welded components become bent or twisted as a consequence of uneven heating and cooling during the welding process. This can result in the welded parts being misaligned.

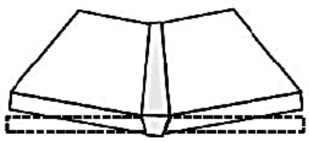


Figure 3.3 angular shrinkage [4]

- Rotational distortion: Rotational distortion in weldings occurs when the weldment undergoes angular displacement during the welding process. This can be caused by various factors, including thermal expansion and contraction, residual stresses and welding technique.

Figure 3.4 rotational shrinkage [4]

- Bowing distortion: Bowing distortion occurs when the welded parts become curved when uneven heating and cooling during the welding process takes place. This can result in the welded parts being misaligned or not fitting properly.

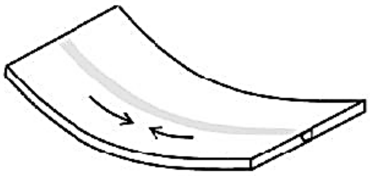


Figure 3.5 bowing shrinkage [4]

- Buckling distortion: can occur during welding when the welded structure is subjected to compressive loads, such as thermal stresses or external loads. This type of distortion can occur in various forms, including angular distortion, bowing, and twisting. Bowing occurs when the weldment bends out of plane, and twisting occurs when the weldment rotates around its axis.

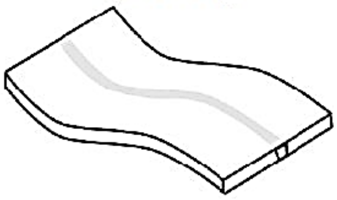


Figure 3.6 buckling shrinkage [4]

3.2 Longitudinal distortion

Longitudinal distortion is a type of welding distortion that occurs along the length of the weld and causes the length of a welded joint to shrink as it cools and solidifies. It is caused by the weld metal shrinking as it cools, resulting in welded components that are longer or shorter than before welding. The heat created by the welding torch or arc causes the metal to expand during the welding process. The metal contracts as it cools, causing the welded junction to shrink longitudinally. Longitudinal distortion can occur in all welding techniques, including arc, gas, and resistance welding. It is more common in thicker materials or during the welding process produces high heat input.

The degree of longitudinal shrinkage in welding is determined by several factors, including the type of metal being welded, the welding procedure utilized, the quantity of heat input, and the thickness of the welded joint. Longitudinal shrinkage can be particularly problematic in long welded structures, such as pipelines or beams, where the shrinkage can cause the structure to buckle or deform.

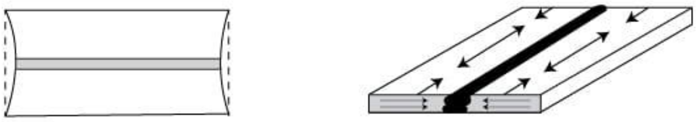


Figure 3.7 Longitudinal distortion [4]

To minimize longitudinal distortion, it is important to use proper welding techniques and parameters. Welders should maintain proper preheat and interpass temperatures to minimize thermal stresses and use appropriate welding techniques to control the heat input. Additionally, the use of clamps, fixtures, and jigs can help to prevent the welded parts from moving or becoming misaligned during the welding process.

If longitudinal distortion does occur, it can often be corrected by applying controlled heat to the affected area and using mechanical methods such as bending or straightening. However, prevention is always preferable to correction, as excessive distortion can result in weld defects, reduce the weld's tensile strength, and compromise the overall quality of the welded connection.

In some cases, welders may intentionally induce longitudinal shrinkage to produce a specific shape or configuration in the welded joint. This technique, known as controlled deformation or post-weld heat treatment, involves heating the welded joint to a set temperature and then slowly cooling down induce the desired shape or configuration.

3.2.1 Types of longitudinal distortion and permitted deviation

Indicative cases of longitudinal distortion and the deviation measured permitted parameters are presented below (taken by EN-1090-2)

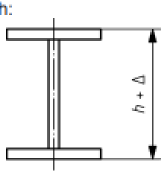
Criterion	Parameter	Permitted deviation Δ
Depth: 	Overall depth h:	$\Delta = -h/50$ (no positive value given)

Figure 3.8 length deviation [8]

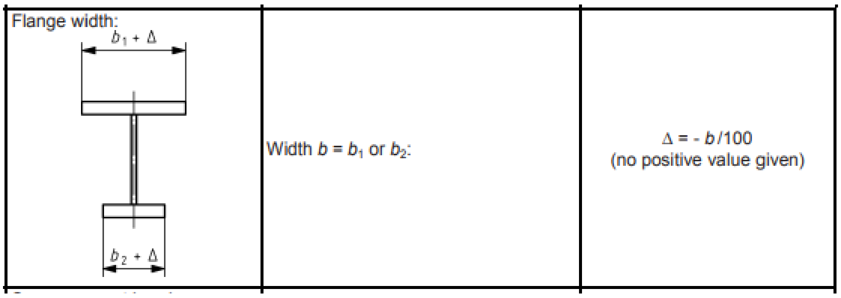


Figure 3.9 width deviation [8]

3.3 Transverse distortion

Transverse distortion is a frequent welding problem that arises when the welded material warps or bends perpendicular to the weld. Transverse shrinkage in welding refers to the decrease in width of the welded junction as it cools and solidifies. The heat created by the welding torch or arc causes the metal to expand during the welding process. The metal contracts as it cools, causing the welded junction to shrink transversely.

A variety of factors, including the type of metal being welded, the welding procedure utilized, the quantity of heat input, the thickness of the welded joint, uneven heating, residual tensions, and the inherent qualities of the materials being welded, can cause this. Welding procedures and techniques are frequently designed to reduce transverse shrinkage in order to avoid distortions, warping, and cracking in the welded joint.

One method of preventing transverse distortion is to utilize suitable welding processes, such as preheating and managing welding parameters such as heat input, welding speed, and weld size and form. Furthermore, utilizing correct fixtures and clamps to keep the material in place when welding might help to reduce distortion.

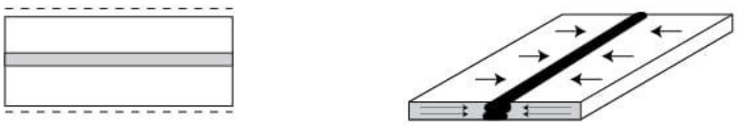


Figure 3.10 transverse distortion [4]

If transverse distortion does occur, there are several methods to correct it, including using heat to straighten the material, applying mechanical force to bend it back into shape, or cutting and rewelding the affected area. However, these methods can be time-consuming and may compromise the structural integrity of the weld.

In summary, preventing transverse distortion is best achieved through proper welding techniques, but if it does occur, it can be corrected using various methods depending on the degree of distortion and the materials being fused. To compensate for transverse shrinkage, welders may use techniques such as preheating the metal, applying weld reinforcement, alternatively, clamps and fixtures can be used to keep the metal in place while welding. Proper welding techniques and the selection of appropriate materials can help minimize transverse shrinkage and ensure a strong, stable welded joint.

3.3.1 Types of transverse distortion and permitted deviation

Indicative cases of transverse distortion and the deviation measured permitted parameters are presented below (taken by EN-1090-2)

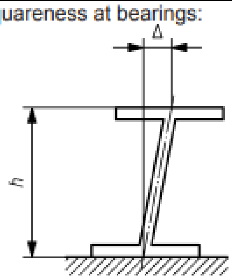
Squareness at bearings: 	Verticality of web at supports, for components without bearing stiffeners:	$\Delta = \pm h/200$ A1 but $\lvert\Delta\rvert \geq t_w$ A1 (t_w = web thickness)

Figure 3.11 verticality deviation [8]

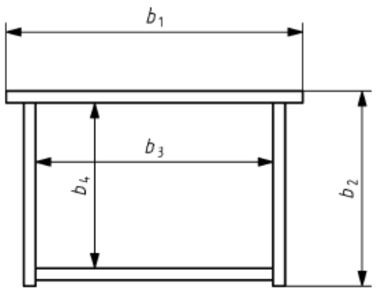
Criterion	Parameter	Permitted deviation Δ
Section dimensions: 	Internal or external dimensions: where: $b = b_1, b_2, b_3$ or b_4	$-\Delta = b/100$ (no positive value given)

Figure 3.12 outer dimensions deviation [8]

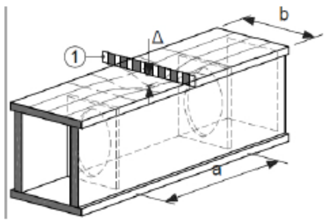
Out of plane imperfections of plate panels between webs or stiffeners (special case with compression in the transverse direction – the general case applies unless this special case is specified):
A1

Key
1 straight edge gauge of length b A1
	Distortion *Δ* perpendicular to the plane of the plate:
	if *b* ≤ 2*a*:
	if *b* > 2*a*:
		
		Δ = ± *b*/250
		Δ = ± *a*/125

Figure 3.13 plate panels deviation [8]

3.4 Angular distortion

Angular distortion is another common type of distortion that can occur in welding. It is the distortion of the welded material that causes it to bend or twist in a direction perpendicular to the weld axis. This is a sort of distortion caused by thermal expansion and contraction during welding, which can lead to uneven stresses in the material. Itis a type of welding distortion that refers to the change in angle or orientation of a welded joint caused by uneven heating and cooling during the welding process. Angular change can occur in any type of welded joint, but it is particularly common in butt joints, T-joints, and lap joints.

If angular distortion does occur, it can be corrected using a variety of methods, such as heat straightening, mechanical force, or cutting and rewelding. However, correcting angular distortion can be more challenging than correcting other types of distortion, and it may require more extensive repairs or even the replacement of the welded component.

Figure 3.14 angular distortion [4]

Angular distortion can be minimized by using proper welding techniques, such as controlling the heat input, preheating the material, and maintaining proper joint fit-up. By holding the material in place during welding and avoiding the effects of thermal expansion, jigs, fixtures, and clamps can also aid to prevent angular distortion. Also, welders may use techniques such as preheating the metal, using a slower welding speed, and applying clamps or fixtures to hold the metal in place during welding. Welders may also use techniques such as backstepping or skip welding, which involve alternating the direction of the weld to distribute the heat more evenly and reduce distortion.

In summary, minimizing angular distortion in welding requires careful consideration of the welding parameters and proper joint fit-up, as well as the use of jigs, fixtures, and clamps. If angular distortion does occur, it can be corrected using various methods, but the repair process may be more complex than for other types of distortion. Proper welding techniques and the use of appropriate materials can also help minimize angular change and ensure a strong, stable welded joint. Welders must carefully monitor the welding process and make adjustments as necessary to minimize distortion and ensure a high-quality weld.

3.4.1 Types of angular distortion and permitted deviation

Indicative cases of angular distortion and the deviation measured permitted parameters are presented below (taken by EN-1090-2)

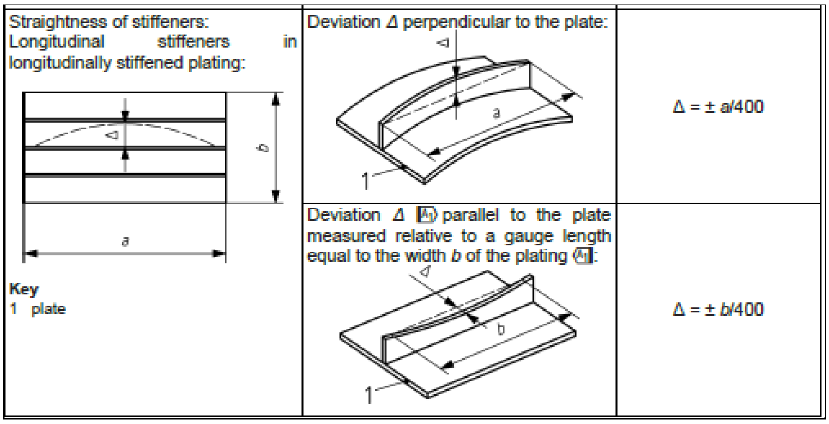


Figure 3.15 straightness of longitudinal stiffeners [8]

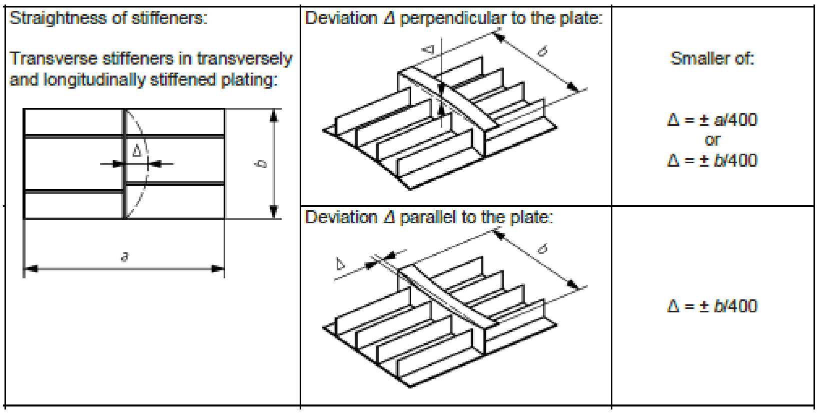


Figure 3.16 straightness of transverse stiffeners [8]

3.5 Rotational distortion

Rotational distortion in weldings occurs when the weldment undergoes angular displacement during the welding process. It is a common type of distortion that can occur in welded joints. It refers to the twisting or bending of a welded joint caused by the uneven distribution of heat and contraction during the cooling process. This can be caused by various factors, including thermal expansion and contraction, residual stresses, and welding technique.

When a weld is made, heat is applied to the material causing it to expand. As the metal cools and contracts, it can cause the weldment to distort or warp. Residual stresses can also cause distortion, as they are created when the metal is welded and can cause the metal to twist or bend. This type of distortion is particularly common in cylindrical or round structures, such as pipes or tanks, where the circular shape of the structure can make it more susceptible to twisting or bending. Several factors, including the quantity of heat input, the speed of the welding process, and the shape of the welded connection, can create rotational distortion. To minimize rotational distortion, welders may use techniques such as preheating the metal, using a slower welding speed, and applying clamps or fixtures to hold the metal in place during welding.

Welding technique can also play a role in rotational distortion. If the welding is done in a haphazard or inconsistent manner, it can cause the weldment to warp or twist. Proper welding techniques, including controlling the heat input, using proper welding speeds, and maintaining proper fit-up and alignment, can help minimize the risk of rotational distortion.

In addition, some welding processes, such as orbital welding, are designed to minimize rotational distortion. Orbital welding uses a rotating torch that moves around the circumference of the welded joint, applying a consistent amount of heat and ensuring even distribution of heat and contraction. Proper welding techniques, the use of appropriate materials, and careful attention to the welding process can help minimize rotational distortion and ensure a strong, stable welded joint

To prevent or minimize rotational distortion in weldings, it is important to take several factors into account. This includes proper preparation of the weldment, including ensuring that the pieces being welded are properly aligned and fit together tightly. Controlling the amount of heat used during the welding process is also critical, since too much heat can cause the metal to expand and deform. Additionally, using proper welding techniques and controlling the cooling rate can help minimize the risk of rotational distortion.

3.5.1 Types of rotational distortion and permitted deviation

Indicative cases of rotational distortion and the deviation measured permitted parameters are presented below (taken by EN-1090-2)

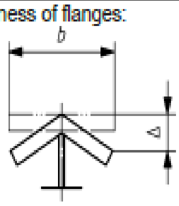
Flatness of flanges: 	Out of flatness: - general case - flange parts in contact with structural bearings	Δ = ± *b*/150 but |Δ| ≥ 3 mm Δ = ± *b*/400	Δ = ± *b*/150 but |Δ| ≥ 2 mm Δ = ± *b*/400

Figure 3.17 flatness of flanges [8]

3.6 Bowing distortion

Bowing distortion is a type of distortion in welding that occurs when the welded material bends or warps along the length of the weld. This sort of distortion is generated by uneven heating and cooling of the welding material, which causes thermal stresses that can cause the material to flex. Bowing distortion can be prevented by using proper welding techniques, such as controlling the heat input, using a proper welding sequence, and maintaining proper joint fit-up. Preheating the material can also help to reduce the effects of thermal stresses and prevent bowing distortion.

If bowing distortion does occur, it can be corrected using a variety of methods, such as heat straightening or applying mechanical force to bend the material back into shape. In some cases, cutting and rewelding may also be necessary to correct the distortion.

To summarize, eliminating bending distortion in welding necessitates careful management of the welding parameters, such as heat input and welding sequence, as well as correct joint fit-up and material preheating. If bowing distortion does occur, it can be corrected using various methods, but the repair process may be more complex and time-consuming than for other types of distortion.

3.6.1 Types of bowing distortion and permitted deviation

Indicative cases of bowing distortion and the deviation measured permitted parameters are presented below (taken by EN-1090-2)

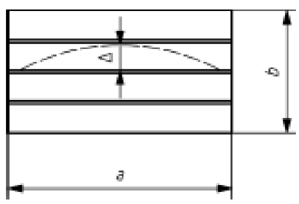
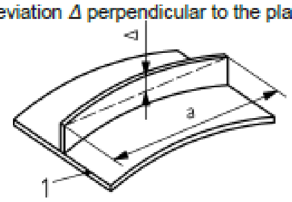
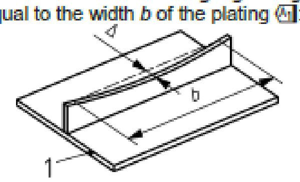
Straightness of stiffeners: Longitudinal stiffeners in longitudinally stiffened plating:  Key 1 plate	Deviation *Δ* perpendicular to the plate: 	Δ = ± *a*/400
	Deviation *Δ* [A1] parallel to the plate measured relative to a gauge length equal to the width *b* of the plating [A1]: 	Δ = ± *b*/400

Figure 3.18 deviation perpendicular and parallel of stiffeners [8]

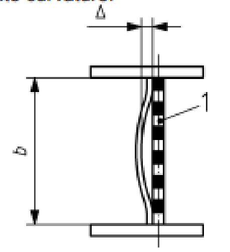
Plate curvature: 	Deviation Δ over plate height b:	[A1⟩ $\Delta = \pm b/200$ if $b/t \leq 80$ $\Delta = \pm b^2/(16\,000\,t)$ if $80 < b/t \leq 200$ $\Delta = \pm b/80$ if $b/t > 200$ but $\lvert\Delta\rvert \geq t$ (t = plate thickness) ⟨A1]

Figure 3.19 curvature deviation [8]

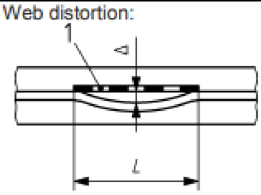
Web distortion: 	Deviation Δ on gauge length L equal to [A1⟩ web height b (see (4)) ⟨A1]:	$\Delta = \pm b/100$ but $\lvert\Delta\rvert \geq t$ (t = plate thickness)

Figure 3.20 deviation of height [8]

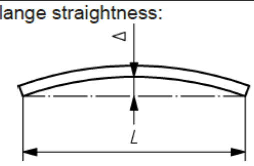
Flange straightness: 	Deviation Δ from straightness	[A1⟩ $\Delta = \pm L / 750$ ⟨A1]	$\Delta = \pm L / 1\,000$

Figure 3.21 flange straightness [8]

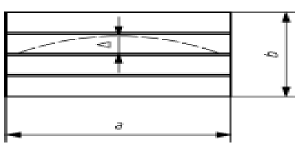
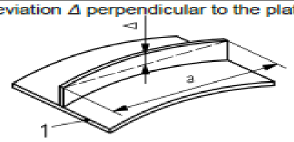
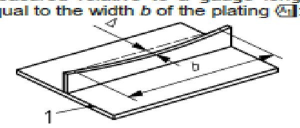
Straightness of stiffeners: Longitudinal stiffeners in longitudinally stiffened plating:  **Key** 1 plate	Deviation Δ perpendicular to the plate: 	$\Delta = \pm a/400$
	Deviation Δ [A1⟩ parallel to the plate measured relative to a gauge length equal to the width b of the plating ⟨A1]: 	$\Delta = \pm b/400$

Figure 3.22 deviation of stiffeners [8]

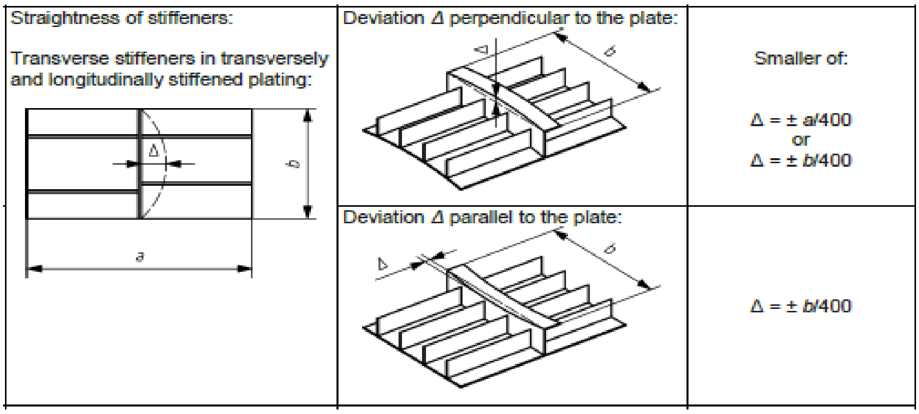


Figure 3.23 straightness of stiffeners [8]

3.7 Buckling distortion

Buckling distortion is a type of welding distortion characterized by the deformation of a welded joint as a result of compressive forces. Buckling distortion can occur when compressive loads applied to a welded joint surpass its capacity, causing it to deform or buckle.

Buckling distortion can be induced by a number of variables, including the type of metal used in the welding, the welding method, and the geometry of the welded joint. It's especially frequent in long, thin structures like columns and pipelines, where compressive pressures can cause the structure to bend or deform.

Welders may utilize procedures such as preheating the metal, providing weld reinforcement, or utilizing clamps and fixtures to hold the metal in place during welding to reduce buckling distortion. Welders may also use techniques such as back stepping or skip welding, which involve alternating the direction of the weld to distribute the heat more evenly and reduce distortion.

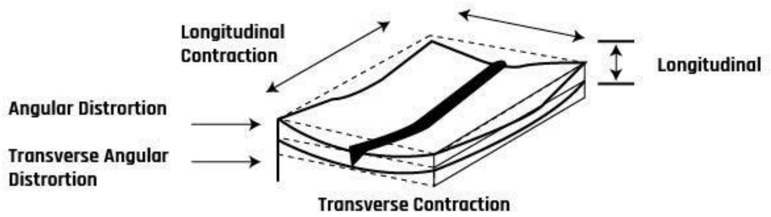


Figure 3.24 buckling [4]

Furthermore, post-weld heat treatment can be employed to correct or reduce buckling distortion. This method entails heating the welded joint to a certain temperature and then progressively cooling it to relieve compressive stresses and prevent buckling.

Proper welding techniques and the use of appropriate materials can also help minimize buckling distortion and ensure a strong, stable welded joint. Welders must carefully monitor the welding process and make adjustments as necessary to minimize distortion and ensure a high-quality weld.

Buckling distortion has serious consequences for the structural integrity and performance of welded structures. It can create stress concentration, diminish the structure's fatigue life, and lead to premature failure.

To prevent buckling distortion in welding, several techniques can be used, such as pre-bending the welded structure, using tack welds to hold the structure in place, controlling the welding sequence, and applying clamps to maintain alignment. Furthermore, choosing the right welding parameters, such as heat input and welding speed, can assist prevent buckling distortion.

3.7.1 Types of buckling distortion and permitted deviation

Indicative cases of buckling distortion and the deviation measured permitted parameters are presented below (taken by EN-1090-2)

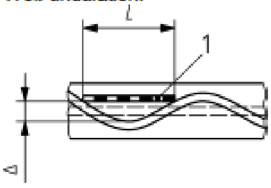
Web undulation: 	Deviation Δ on gauge length *L* equal to [A1] web height *b* (see (4)) [A1]:	$\Delta = \pm b/100$ but $\|\Delta\| \geq t$ (t = plate thickness)

Figure 3.25 deviation of undulation [8]

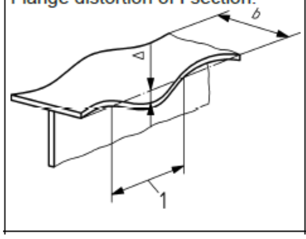
Criterion	Parameter	Permitted deviation Δ
Flange distortion of I section: 	Distortion Δ on gauge length *L* where *L* = flange width *b*	[A1] $\Delta = \pm b/150$ if $b/t \leq 20$; $\Delta = \pm b^2/(3\,000\,t)$ if $b/t > 20$; t = flange thickness [A1]

Figure 3.26 flange distortion [8]

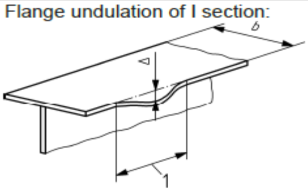
Flange undulation of I section: 	Distortion Δ on gauge length L where L = flange width b	A1) $\Delta = \pm\, b/150$ if $b/t \le 20$ $\Delta = \pm\, b^2/(3\,000\, t)$ if $b/t > 20$ t = flange thickness (A1

Figure 3.27 flange undulation [8]

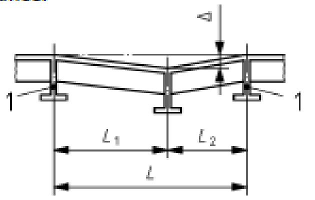
Levels of cross frames in stiffened plating: **Key** 1 cross member	Level relative to the adjacent cross frames: 	$\Delta = \pm\, L / 400$

Figure 3.28 levelling deviation [8]

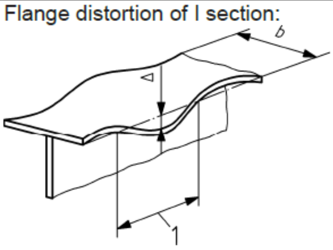
Flange distortion of I section: 	Distortion Δ on gauge length = flange width b	$\Delta = \pm\, b / 100$	$\Delta = \pm\, b / 150$

Figure 3.29 flange distortion [8]

3.8 Overall general conclusions and corrective actions for distortions

The following table includes general directions for the connection between causes and remedies [9]. Further investigation will be presented on a separate chapter.

Table 3.1 distortion type, causes and remedies [9]

Distortion Type	Causes	Remedies
Transverse Shrinkage	Weld metal hardness problem, constraints applied to weld-joints.	Weld Metal hardness should be sufficient.
Longitudinal Shrinkage	Preheat or fast cooling problem	Weld Short length. Apply sufficient preheat.
Rotational Distortion	Uneven heat flow	Temperature of heat source should be sufficient; weld speed should not be too slow.
Angular Distortion	High amount of heat input	Reduce volume of weld metal, Apply Preheat and post weld treatment.
Bending	Excessive root gaps, excessive heat input.	The root gap should be kept optimum, Double-V Preparation should be done while welding heavy sections
Buckling	Excessive specimen length	Critical length for a given thickness should be considered.

3.9 Distortions and tolerances

From all the above types of welding distortions the tolerances for any kind of measuring dimension are given in EN 13920[5] with following general tolerances tables in welded structures.

Table 3.2 tolerances for linear dimensions [10]

Tolerance class	Range of nominal sizes l in mm										
	2 to 30	Over 30 up to 120	Over 120 up to 400	Over 400 up to 1 000	Over 1 000 up to 2 000	Over 2 000 up to 4 000	Over 4 000 up to 8 000	Over 8 000 up to 12 000	Over 12 000 up to 16 000	Over 16 000 up to 20 000	Over 20 00 0
	Tolerances t in mm										
A	± 1	± 1	± 1	± 2	± 3	± 4	± 5	± 6	± 7	± 8	± 9
B		± 2	± 2	± 3	± 4	± 6	± 8	± 10	± 12	± 14	± 16
C		± 3	± 4	± 6	± 8	± 11	± 14	± 18	± 21	± 24	± 27
D		± 4	± 7	± 9	± 12	± 16	± 21	± 27	± 32	± 36	± 40

Table 3.3 tolerances for angular dimensions [10]

Tolerance class	Range of nominal sizes l in mm (length or shorter leg)		
	Up to 400	Over 400 up to 1 000	Over 1 000
	Tolerances Δα (in degrees and minutes)		
A	± 20′	± 15′	± 10′
B	± 45′	± 30′	± 20′
C	± 1°	± 45′	± 30′
D	± 1°30′	± 1°15′	± 1°
	Calculated and rounded tolerances t, in mm/m[a]		
A	± 6	± 4,5	± 3
B	± 13	± 9	± 6
C	± 18	± 13	± 9
D	± 26	± 22	± 18

[a] The value indicated in mm/m corresponds to the tangent value of the general tolerance. It is to be multiplied by the length, in m, of the shorter leg.

Table 3.4 straightness, flatness and parallelism tolerances [10]

Range of nominal sizes l in mm (relates to longer side of the surface)										
Tolerance class	Over 30 up to 120	Over 120 up to 400	Over 400 up to 1 000	Over 1 000 up to 2 000	Over 2 000 up to 4 000	Over 4 000 up to 8 000	Over 8 000 up to 12 000	Over 12 000 up to 16 000	Over 16 000 up to 20 000	Over 20 000
	Tolerances t in mm									
E	0,5	1	1,5	2	3	4	5	6	7	8
F	1	1,5	3	4,5	6	8	10	12	14	16
G	1,5	3	5,5	9	11	16	20	22	25	25
H	2,5	5	9	14	18	26	32	36	40	40

Staying and applying on the general directions on the above tolerances will be crucial for the welded structures not only on the erection process but also on the vitality of the longlife of the total welded structure. Therefore, they should be followed by the whole fabrication process at each separate subprocess state.

4 Effect of welding parameters on welding distortions

4.1 Introduction in welding parameters

The advancement of the industrial world today is affecting the economies of countries and the well-being of workers. On the one hand, the deployment of new equipment will facilitate the production process and increase worker productivity. On the other hand, it has the potential to worsen worker health and safety hazards associated with the job relationship. The building sector's technological progress is more advanced, which cannot be separated from welding because it plays a significant role in engineering and metal repair. At the moment, metal building involves a lot of welding, especially in the construction design sector for welding joints is one of making connections that technically requires high welding expertise in order to produce a welding connection of good quality. Welding techniques are used in a wide range of construction applications, including ships, bridges, steel structures, pressure vessels, transportation, rail, pipelines, and others. The welding technique, which is a plan for the implementation of the research and covers how to produce welding construction in accordance with plans and requirements, is one of the factors affecting the welding.

Welding is a widely utilized arc welding technology that was developed in the early 1940s to satisfy the needs of large fabrication sectors such as ship welding. Since then, the procedure has grown in popularity due to its capacity to be mechanized and create long continuous joints on these parts. It is also suitable for horizontal circumferential butt welds on pipes, pressure tanks, and rail carriages, and has a wide industrial application.

Distortion is unavoidable in the welding process and is a serious issue. By regulating the welding parameters, distortion might be reduced up to a certain limit. Thermal stresses and angular distortion in a welding joint are caused by the expansion and contraction of the welding metal and the adjacent base metal throughout the welding process's heating and cooling cycles. The geometry of a weld is determined by the welding parameters. The weld shape is critical in the distortion of welded components. The effect of welding process parameters such as shielding gas flow rate, welding electrode weaving motion, and torch angle on the profiles and distortion of steel plates of varying thicknesses. The distortion diminishes as the torch angle increases, but it increases as the gas flow rate increases. The intended weld width, the vertical motion period in the welding direction, and the lateral motion speed normal to the welding direction comprise the electrode weaving motion. The distortion decreases as the weld width and vertical motion period increase, but increases when the lateral speed decreases.

The weld metal and nearby base metal heterogeneity heat and cool during every welding procedure. Meanwhile, the weld zone experiences heterogeneous expansion and contraction, resulting in thermal stresses. At the solidification temperature, the weld metal size is at its maximum. The weld metal contracts as it cools, but it is held back by the nearby base metal. As a result, tensions form within the weld and the neighboring base metal. Weld shrinkage strains create six types of deformities in weldments. When the shrinkage forces are perpendicular and parallel to the weld, the shrinkage types transverse and longitudinal occur. When non-uniform shrinkage forces are produced through the thickness, a resultant force is generated in the weld metal's centroid. When this centroid differs from the centroid of the transverse cross section of the base metal, a bending moment arises, warping the plate. Angular distortion is a common welding flaw that leads to costly repairs in steel structures.

The weld shape is crucial because it determines the amount of shrinkage and the internal shrinkage stresses caused. The contraction stresses determine the size and direction of the angular distortion. The bending moment at each weld metal point is calculated by multiplying the contraction force by the distance between that point and the plate's centroid. The resulting bending moment of all weld metal points equals the weld's resultant bending moment. Because each weld has a unique weld bead, different contraction stresses and bending moments can be produced after the welding process. When the distance between the weld bead's centroid and the plate is short, a modest bending moment and angular distortion result. Welding parameters have an impact on bead geometry.

Welding distortions can be generated by a variety of reasons, such as the welding process, welding settings, and material qualities. Welding parameters are divided into primary and secondary parameters. The key parameters are the welding current, welding speed, welding voltage, electrode size and shape, preheat temperature, and post-weld heat treatment, all of which directly affect the weld pool profile and weld form. Secondary characteristics have an indirect effect on weld bead shape. They vary the primary parameters, which affects the weld shape. These parameters are arc distance, torch angle, shielding gas chemical composition, gas flow rate, and electrode polarity.

4.2 Welding parameters

According to the Deutsche Industrie Norman (DIN), welding is a metallurgical bond at the junction of a metal or metal alloy that is performed while the metal or metal alloy is molten or liquid. In other terms, welding is the use of heat energy to form a local connection between numerous metal rods. According to the AWS (American Welding Society), welding is the process of joining materials by heating them until they achieve a welding temperature, with or without the application of pressure or a filler metal. Primary and secondary welding parameters that can impact welding distortions include:

4.2.1 Primary welding parameters

Primary welding parameters include:

- interpass temperature
- base metal thickness
- welding sequence
- welding current
- welding speed
- welding voltage
- electrode size and shape
- pre-heat temperature

- post-weld heat treatment

4.2.1.1 Interpass temperature

The temperature of the base metal between welding passes during a multi-pass welding operation is referred to as interpass temperature. Controlling the interpass temperature ensures that the weld metal and base metal are not overheated, which can cause cracking, distortion, or loss of mechanical qualities.

The precise interpass temperature needed for a welding project is determined by various factors, including the base metal type, welding method, and welding technique. Interpass temperatures are often set by the welding code or standard being used, or by the welding procedure specification (WPS) produced for the specific project.

The heat input from consecutive weld passes can cause the temperature of the previously welded joint to rise during multi-pass welding. If the interpass temperature exceeds the required limit, it can create a variety of weld flaws, including hydrogen-induced cracking and lower toughness. To maintain the integrity of the welded joint, it is critical to regulate the interpass temperature by preheating, adjusting the welding settings, and cooling between passes.

The temperature of the interpass is an important component in controlling welding distortion. Welding distortion is the deformation of the base metal caused by uneven heating and cooling during the welding process. When the temperature of the base metal is not correctly regulated during welding, thermal tensions that induce distortion can occur.

To minimize welding distortion, the interpass temperature should be maintained within the specified range. If the interpass temperature is too high, it can cause the base metal to expand and lead to buckling or warping. On the other hand, if the interpass temperature is too low, the weld metal may not penetrate properly into the base metal, leading to incomplete fusion and weaker welds.

In addition to controlling the interpass temperature, other techniques can also be used to minimize welding distortion, such as using tack welds to hold the parts in place before welding, balancing the welding sequence to distribute the heat input evenly, and using fixtures or clamps to restrict movement during welding.

Overall, controlling the interpass temperature is an essential step in reducing welding distortion and ensuring the quality of the welded joint.

4.2.1.1 Base metal thickness

Base metal thickness can be a significant factor in causing distortion during welding or other types of metal joining processes. The amount of heat required to melt and fuse the metal increases as the thickness of the base metal increases. This can result in a greater amount of residual heat, which can cause the metal to expand and contract during cooling, leading to distortion.

Thicker base metals also have a greater mass, which can result in a longer cooling time. During this cooling period, the metal can undergo significant changes in shape due to the residual stresses generated on the process of welding. Distortion will come up, particularly in areas where the weld has concentrated heat. Therefore, when welding or joining thicker base metals, it is important to carefully consider the welding parameters and techniques used to minimize distortion. This aims to minimize the amount of residual heat in the metal.

Table 4.1 Results of an experimental method for different thickness and distortion results [11]

Plate Thickness (mm)	Welding Current (Ampere)	Welding Voltage (Volt)	Welding Speed (mm/min)	Heat Input (kJ/mm)	Angular Distortion (mm)
10	151	21	121	3.8	2.3
16	194	29	158	9.7	7,9
20	209	29	185	11.8	9,6
10	118	21	104	4.9	4.1
16	184	28	128	9.7	9.3
20	199	28	155	12.06	10.6

4.2.1.2 Welding sequence

The welding sequence is a critical welding characteristic that can have a considerable impact on distortion in welded structures. When the thermal expansion and contraction of the material during the welding process lead the welded structure to deform or bend, this is referred to as distortion. The welding sequence is the order in which welds are made and can affect the distribution of residual stresses and temperature gradients in the welded structure.

One method for reducing distortion is to adopt a welding sequence that balances the structure's residual stresses. A balanced welding sequence, for example, could involve alternating the direction of welding between opposing sides of the structure or welding from the center outwards. This can help to keep one side of the structure from undergoing more heat expansion and contraction than the other, which can lead to distortion.

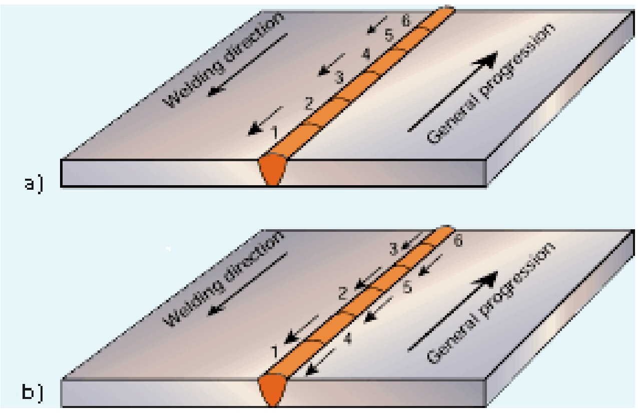


Figure 4.1 Welding direction in order to control distortion a) back step welding b) skip welding [12]

Another approach to minimizing distortion is to use a welding sequence that minimizes the heat input to the material. This can be achieved by using a smaller welding electrode or reducing the welding speed. By minimizing the heat input, the amount of thermal expansion and contraction in the material can be reduced, which can in turn reduce distortion.

Overall, the welding sequence used will be determined by the specific welding application and the welded structure's requirements. By carefully selecting a welding sequence and other welding parameters, it is possible to minimize distortion and produce a high-quality welded structure.

4.2.1.3 Welding current

The electrical current used to generate the heat required for welding is known as welding current. When welding, an electric arc is formed between the electrode (or welding wire) and the workpiece, generating extreme heat that melts and fuses the metal together. The welding and the electrode or welding wire diameter. Higher currents are generally necessary for thicker metals and welding methods requiring more heat input, such as MIG (Metal Inert Gas) and TIG (Tungsten Inert Gas) welding.

Welding current is typically measured in amperes (A), and the appropriate welding current for a particular welding job can be determined by consulting welding tables or by following the recommendations of the welding machine manufacturer. To ensure a robust, long-lasting weld, utilize the correct welding current for the job at hand. The welding current influences the amount of heat applied to the welded material. Higher welding currents can provide more considerable heat input, resulting in higher amounts of distortion.

One of the parameters that can influence welding distortion is welding current. Welding distortion is the deformation of the welded metal caused by thermal expansion and contraction during the welding process. Dimensional inaccuracies and other quality concerns in the welded product can emerge from this distortion.

Higher welding currents can result in greater heat input and can cause more significant thermal expansion and contraction in the metal being welded. This can increase the risk of welding distortion. However, lower welding currents may not provide enough heat to produce a strong and effective weld.

Current is typically provided by a welding machine, which delivers the current to the electrode or welding wire.

The amount of current required for welding is determined by several factors, including the type and thickness of the metal being welded, as well as the welding procedure utilized.

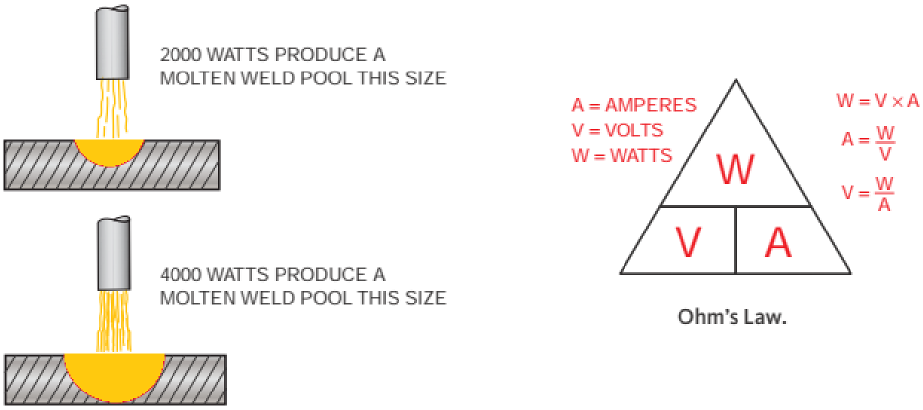


Figure 4.2 effect of welding current [13]

The effect of welding current on welding distortion is also affected by other welding parameters such as welding speed, metal type and thickness, and welding technique. The interaction of these elements can be complex, therefore optimizing the welding parameters to reduce welding distortion is critical.

To reduce welding distortion, the welding current must be properly controlled. By carefully controlling this, it is possible to minimize welding distortion and produce high-quality welds.

4.2.1.4 Welding speed

Welding speed is the rate at which a weld is produced, and it is one of the important characteristics that influences welding quality and efficiency. Welding speed is usually measured in inches per minute (IPM) or centimeters per minute (CPM), and it has a big impact on weld quality.

When the welding pace is too slow, the heat input into the metal becomes excessive, causing distortion, warping, or even burn-through of the metal being welded. If the welding speed is too high, the weld may not penetrate deeply enough into the metal, resulting in a weak or ineffective weld.

The appropriate welding speed is determined by several parameters, including the type and thickness of the metal being welded, the welding procedure employed, and the type of electrode or welding wire used. Higher welding speeds are often attainable with thinner metals, whereas larger metals may necessitate slower welding speeds to guarantee sufficient heat input.

To obtain a high-quality weld, it is critical to determine the optimum welding speed for the project at hand. The welding speed can be changed by manipulating the travel speed of the electrode or welding wire, as well as other welding parameters such as welding current and voltage.

Welding speed is the speed at which the welding torch moves across the material being welded. A slower welding speed can result in more significant heat input and increased distortion.

Welding speed is one of the key parameters that can affect welding distortions. Welding distortions are the deformations that occur in the metal being welded due to thermal expansion and contraction during the welding process. The amount of distortion depends on various factors, including the welding speed.

If the welding speed is too slow, the weld puddle may become too large and the heat input into the metal can be excessive. This can result in a higher risk of welding distortions, including buckling, warping, and shrinkage. On the other hand, if the welding speed is too fast, the heat input into the metal may be insufficient to create a strong and effective weld.

In general, a balance must be struck between welding speed and other parameters to achieve a high-quality weld while minimizing welding distortions.

For instance [14], varying parameters used in the weaving motion experiments and the obtained angular distortion values. In these experiments, the wire feed speed was 6 m/min, the arc voltage was 25 volts, the welding speed was 6 mm/s, the gas flow rate was 12 L/min, and the torch angle was kept constant 90°. In the experiments, the weld width was either 10 mm or 20 mm, the *x*-axis welding speed was 20 or 25 mm/s, and the travel time on the *y*-axis was changed to 0.6–0.9 s. The obtained angular distortion test results are shown in Table 4.2. Figures 4.3–4.5 are drawn by using the results of Table 4.2.

Table 4.2 Distortion and welding speed [14]

Weld width (*x*) (mm)	**Movement duration in *y*-axis (s)**	**Movement speed in *x*-axis (mm/s)**	**Vertical displacement (mm)**
10	0.6	20	1.41
10	0.9	20	1.58
20	0.6	20	1.77
20	0.9	20	1.98
10	0.6	25	1.12
10	0.9	25	1.45
20	0.6	25	1.51
20	0.9	25	1.63

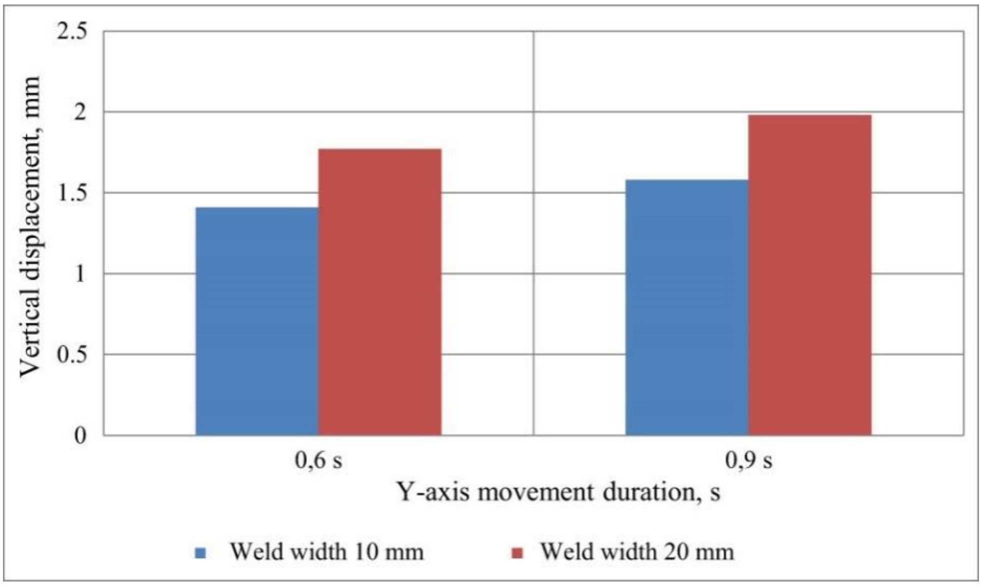


Figure 4.3 the influence of weld width and y-axis movement duration on the angular distortion of plates welded with 20 mm/s x-axis welding speed extracted by results in table 4.2[14]

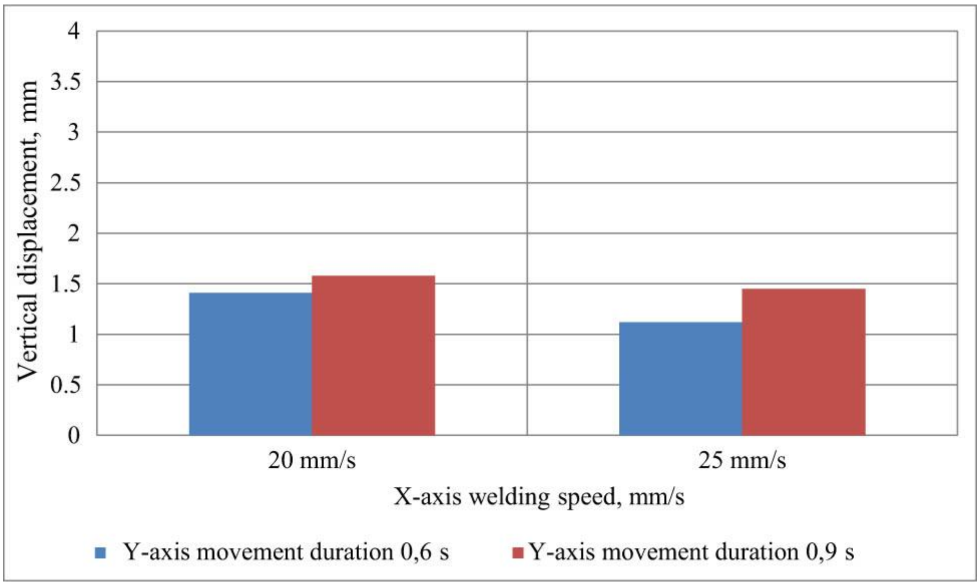


Figure 4.4 how y-axis movement duration and x-axis welding on the angular distortion of 10 mm wide weld plates extracted by results in table 4.2[14]

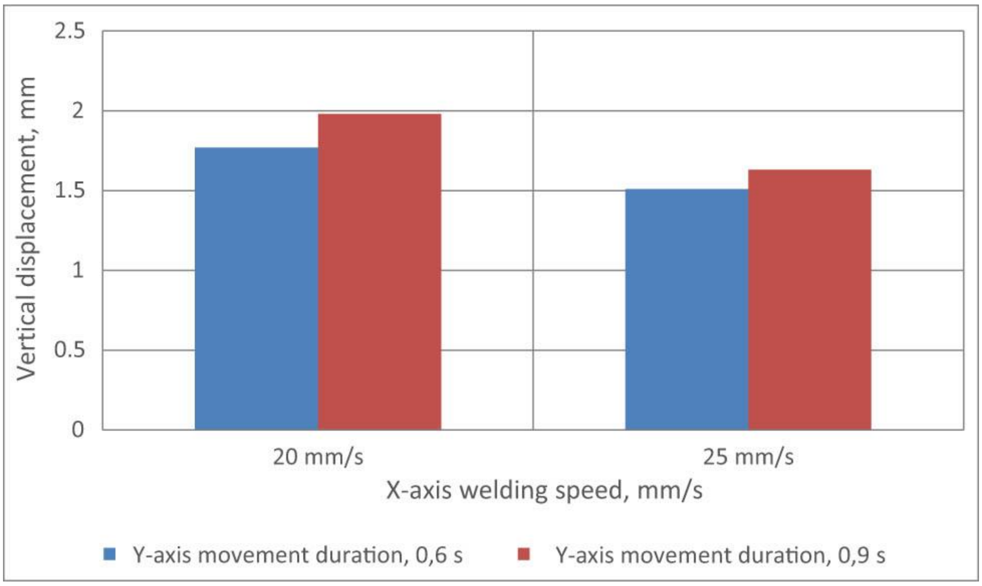


Figure 4.5 the effect of y-axis movement duration and x-axis welding speed on the angular distortion of 20 mm wide weld plates extracted by results in table 4.2[14]

4.2.1.5 Welding voltage

Another critical element in the welding process is the welding voltage. It is the difference in electrical potential between the welding electrode (or welding wire) and the workpiece. When an electric arc is formed between the electrode and the workpiece, the voltage determines the arc's strength and the quantity of heat produced.

The best welding voltage is determined by the type and thickness of the metal being welded, the welding procedure, and the electrode size. Higher welding voltages are generally necessary for thicker metals and welding methods requiring more heat input, such as MIG (Metal Inert Gas) welding.

If the welding voltage is too low, the arc will be insufficiently intense to generate a strong and effective weld, and the weld will be partial or weak. On the other side, if the welding voltage is too high, it can result in too much heat being injected into the metal, causing distortion, warping, or even burn-through of the metal being welded.

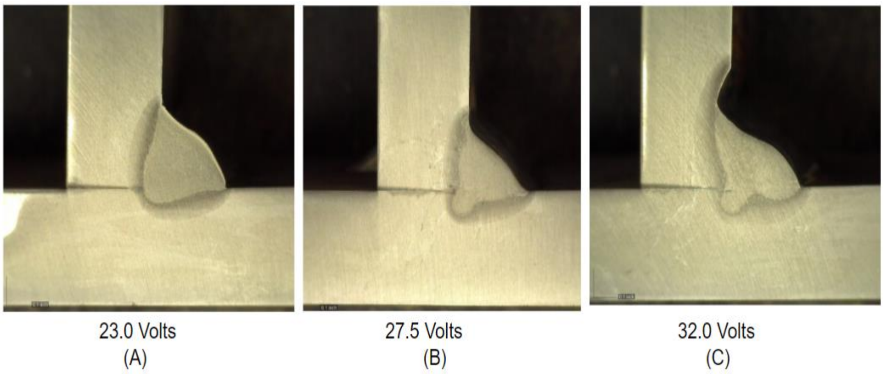


Figure 4.6 these welds were made with ER70S-6 wire, 90% Argon /10% Carbon Dioxide shielding gas at 375 ipm wire feed speed. The only difference was the voltage[15].

The welding voltage can be changed by modifying the distance between the welding electrode and the workpiece, as well as other welding parameters including welding current and travel speed. To obtain a high-quality weld, it is critical to pick the optimum welding voltage for the operation at hand.

One of the components that can effect welding distortion is the welding voltage. Welding distortion is the deformation of the welded metal caused by thermal expansion and contraction during the welding process. The amount of distortion is determined by a number of elements, including the welding voltage.

If the welding voltage is too high, the heat input into the metal can be excessive, which can cause distortion, warping, or even burn-through of the metal being welded. High voltage can also result in a larger weld pool, which increases the risk of welding distortions such as buckling, warping, and shrinkage. On the other side, if the welding voltage is too low, the weld will be weak and ineffective.

The ideal welding voltage is determined by a number of factors, including the type and thickness of the metal being welded, the welding method employed, and welding parameters such as welding current and travel speed. In general, a balance must be struck between welding voltage and other parameters to achieve a high-quality weld while minimizing welding distortions.

To minimize welding distortions, it is important to select the appropriate welding voltage based on the characteristics of the metal being welded and the welding process being used. By carefully adjusting the welding parameters and the distance between the welding electrode and the workpiece, the welding voltage may be optimized. Additionally, using proper fixturing or jigs to hold the metal in place during welding can also help minimize welding distortions.

The electrical potential difference between the welding electrode and the workpiece is referred to as welding voltage. Higher welding voltages can result in higher levels of heat input, leading to more significant distortions.

4.2.1.6 Electrode size and shape

In welding, the size and shape of electrodes determine the quality and efficiency of the welding process. The choice of electrode size and shape is typically play a crucial role by the type of welding technique and the characteristics of the materials to be welded.

In shielded metal arc welding (SMAW), the size of the electrode is directly related to the amount of current it can carry. Larger electrodes can handle higher currents, which can result in higher deposition rates and faster welding speeds. However, larger electrodes also tend to produce larger weld beads, which may not be suitable for certain applications. Conversely, smaller electrodes are typically used for welding thinner materials or for welding in tight spaces.

In gas tungsten arc welding (GTAW), also known as TIG welding, the size and shape of the electrode can impact the stability and quality of the arc. Tungsten electrodes with pointed tips are typically used for welding thin materials, while electrodes with truncated or flat tips are more suited for welding thicker materials. The shape of the electrode can also affect the shape and penetration of the weld bead.

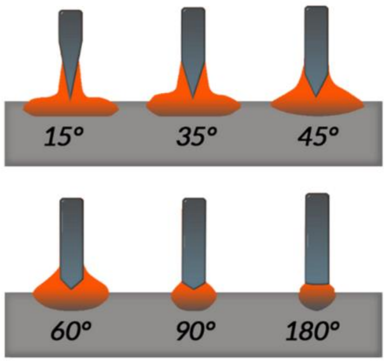


Figure 4.7 Image showing tungsten tip angles and resulting arc width and penetration [16]

Overall, the size and form of the electrodes used in welding will be determined by the welding technique and the materials being welded. When choosing electrodes, consider the required current capacity, the desired welding speed, and the weld bead characteristics.

Welding distortion, which happens as a result of thermal expansion and contraction during the welding process, can also be affected by the size and form of electrodes. The size and shape of the electrode can aid to reduce welding distortion and generate a more uniform weld.

In general, smaller electrodes can produce a narrower and more focused heat input, which can help to reduce welding distortion. This is because smaller electrodes require less current to generate the necessary heat, which results in a smaller heat-affected zone (HAZ) and less thermal expansion and contraction. Additionally, smaller electrodes can be used to weld thinner materials, which can attribute in reducing welding distortion.

The shape of the electrode can also impact welding distortion. For example, a pointed electrode can produce a more focused heat input and reduce the size of the HAZ, which can help to minimize welding distortion. In contrast, a flat or rounded electrode can produce a wider and less focused heat input, which can increase the size of the HAZ and lead to greater welding distortion.

Overall, the choice of electrode size and shape in welding should be based on the specific welding process and the desired outcome, including the need to minimize welding distortion. When choosing electrodes, consider the thickness of the materials to be welded, the desired weld quality, and the welding parameters, such as current and voltage.

The size and shape of the welding electrode can also affect welding distortions. A larger electrode can provide more heat input, leading to more significant distortions.

4.2.1.7 Preheat temperature

Preheat temperature is an important parameter in welding that can have a major impact on weld quality and integrity. Preheating is the process of heating the base metal to a specific temperature prior to welding. It is often used to lessen the danger of cracking and deformation, as well as to improve weld quality.

The preheat temperature required for a certain welding process is determined by various factors, including the material being welded, its thickness, and the welding technique utilized. Preheat temperatures are generally greater for thicker materials and more complicated shapes.

The preheat temperature can be determined through various methods, such as by referring to industry standards and guidelines or through preheat calculations. Preheat calculations take into account the material thickness, joint geometry, and the type of welding process being used, among other factors.

In general, preheating serves to reduce the temperature gradient across the weld, which can help to minimize the risk of cracking and distortion. Furthermore, preheating can serve to improve the metallurgical properties of the weld, such as lowering the danger of hydrogen-induced cracking and increasing weld toughness.

Overall, preheat temperature is an important parameter in welding that should be carefully considered and optimized for each specific welding process and application. Proper preheat can help to ensure a high-quality, defect-free weld and can improve the overall integrity and longevity of the welded structure.

Preheating the material before welding can reduce welding distortions by reducing thermal stresses. Higher preheat temperatures can result in reduced distortions.

Preheat temperature can also have an impact on welding distortion. As mentioned earlier, preheating serves to reduce the temperature gradient across the weld, which can help to minimize the risk of cracking and distortion. By reducing the temperature gradient, preheating can also help to reduce residual stresses that can lead to welding distortion.

In general, higher preheat temperatures can help to reduce welding distortion. Higher preheat temperatures can aid to prevent thermal expansion and contraction during the welding process by reducing the thermal gradient between the weld and the surrounding base metal. Additionally, higher preheat temperatures can improve the fluidity of the weld pool, which can help to distribute heat more evenly and reduce the risk of welding distortion.

However, extremely high preheat temperatures can cause difficulties such as over-softening of the base metal, excessive oxidation, and lower weld strength. As a result, the preheat temperature should be tuned for each unique welding method and application to strike a balance between the need to reduce welding distortion while retaining the requisite weld quality.

Overall, preheat temperature is an important parameter in welding that should be carefully considered and optimized to reduce welding distortion. By reducing the temperature gradient and residual stresses, preheating can help to produce a high-quality, distortion-free weld.

4.2.1.8 Post-weld heat treatment

Post-weld heat treatment (PWHT) is a welding procedure that is commonly used to improve weld characteristics and reduce the risk of failure. PWHT entails heating the welded structure to a set temperature and then cooling it at a regulated rate. This method can help to reduce residual stresses, increase weld ductility and toughness, and reduce cracking risk.

The requirement for PWHT is determined by a number of parameters, including the type of material being welded, the welding process employed, the material thickness, and the intended application of the welded structure. Some materials, such as certain types of high-strength steels, may be more prone to cracking if they are not properly heat treated after welding.

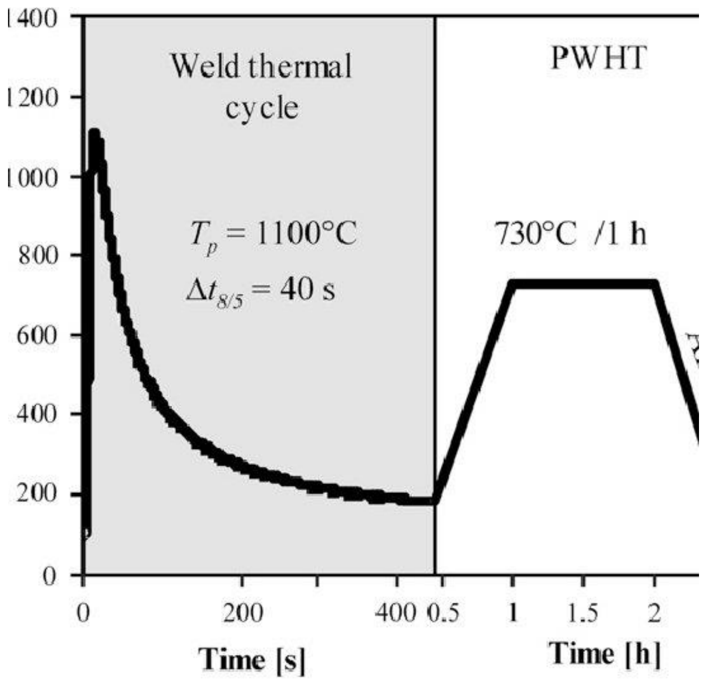


Figure 4.8 schematic of the welding thermal cycle and PWHT [17]

The temperature and time required for PWHT will vary depending on the material being welded and the welding method employed. PWHT is typically heated to temperatures ranging from 500 to 1,200 degrees Celsius [17], and the duration can range from a few minutes to several hours.

It should be noted that PWHT is not always required or appropriate for every welding application. In some cases, it may be more appropriate to use alternative methods of reducing residual stresses, such as peening or grinding. Additionally, some materials may be more sensitive to PWHT and may experience unwanted changes in their properties if they are subjected to excessive heat.

Overall, the decision to use PWHT in welding should be based on a careful evaluation of the specific application, the material being welded, and the process of welding that is being used.

Post-weld heat treatment can also reduce welding distortions by relieving residual stresses in the welded material. Proper post-weld heat treatment can significantly reduce the magnitude of welding distortions.

PWHT is a heat treatment procedure that is commonly used in welding to reduce or eliminate welding distortion. Distortion is a common problem in welding, particularly in large or complex structures. It occurs when the thermal expansion and contraction that occurs during welding causes the material to deform or buckle.

PWHT entails heating the welded material to a certain temperature and keeping it at that temperature for a set period of time, usually several hours. This heat treatment is intended to reduce residual tensions created by the welding process. When the material expands and contracts during the welding process, residual stresses are formed, which can cause distortion.

PWHT can help to minimize distortion and enhance weld quality by easing these stresses. Furthermore, PWHT can aid to increase the welded material's mechanical qualities, such as strength, toughness, and ductility.

The temperature and time of the PWHT process will vary depending on the type of material being welded, the welding procedure employed, and the project's specific requirements. Multiple PWHT cycles may be required in some circumstances to attain the desired outcomes.

Overall, PWHT is a useful tool for decreasing welding distortion and enhancing welded structure quality and mechanical qualities. Working with an experienced welding technician who can identify the optimum PWHT settings for your unique job is critical.

4.2.2 Secondary parameters

Secondary parameters include the following:

- arc distance
- torch angle
- chemical composition
- gas flow rate
- electrode polarity

4.2.2.1 Arc distance

Arc distance can also have an impact on distortion during welding. Distortion refers to shape alteration or dimension of the product that occurs as a result of welding. When the arc distance is too large, it can result in a higher amount of heat input to the workpiece. This can cause the metal to expand and contract in a non-uniform manner, leading to distortion.

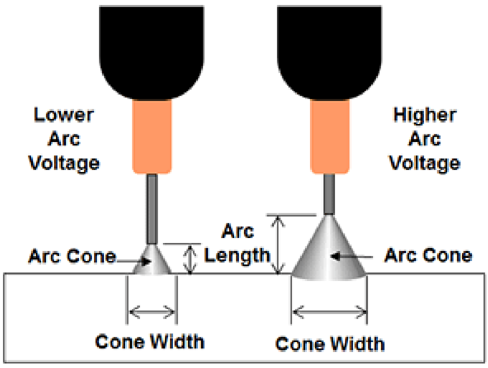


Figure 4.9 Effect of arc distance [18]

There is no relation between arc length and electrode diameter. When diameter increase it is quite difficult to manipulate the arc with higher arc length so welders prefer the lower arc length. Each welder has their own welding style and comfort zone of work, so it depends on welder about the arc length. However, there is a small relation when electrode diameter is more and higher arc length is maintained then cone width of weld pool increases rapidly.

On the other hand, if the arc distance is too small, it can result in a higher concentration of heat in a smaller area, which can cause localized distortion. Additionally, a small arc distance may cause the electrode or filler wire to become stuck or "stuck" to the workpiece, resulting in further distortion and potentially damaging the electrode or filler wire.

To minimize distortion during welding, it is important to carefully control the arc distance and adjust it as necessary based on the conditions of the welding and the properties of the workpiece to be welded. This will help to ensure that the heat input is distributed evenly and that the welding process produces a high-quality, distortion-free weld.

4.2.2.2 Torch angle

Torch angle is another important parameter in welding that can affect distortion. Torch angle refers to the angle at which the welding torch or gun is held relative to the workpiece being welded.

When angle torch is too high, meaning the torch is held too far from the workpiece or at too steep of an angle, it can result in a higher amount of heat input to the workpiece. This can cause the metal to expand and contract in a non-uniform manner, leading to distortion.

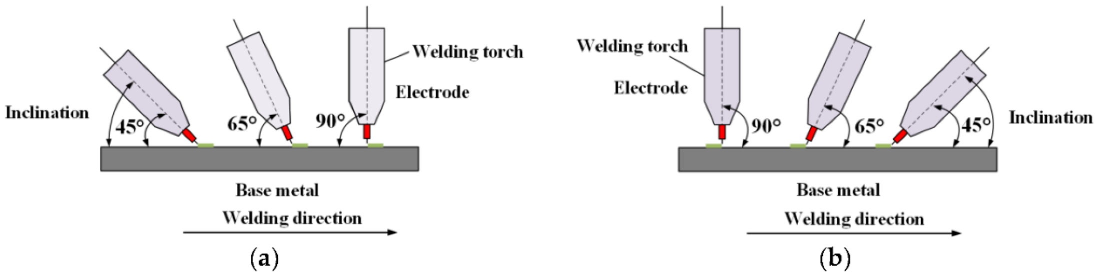


Figure 4.10 Presentation of two inclination modes (a) forward angle, (b) backward angle [19]

Conversely, when the torch angle is too low, meaning the torch is held too close to the workpiece or at too shallow of an angle, it can result in a higher concentration of heat in a smaller area, which can cause localized distortion.

To minimize distortion during welding, it is important to maintain a consistent torch angle throughout the welding process. The ideal torch angle will vary depending on the process of welding being used, the properties of the workpiece and the position of welding. Welders should be trained to use the correct torch angle and make adjustments as necessary to minimize distortion and produce a high-quality, defect-free weld.

4.2.2.3 Chemical composition

The chemical composition of the welding shielding gas might also have an effect on distortion. Shielding gas is used to keep the welding region safe from ambient gases like oxygen and nitrogen, which can cause oxidation and other issues during the welding process.

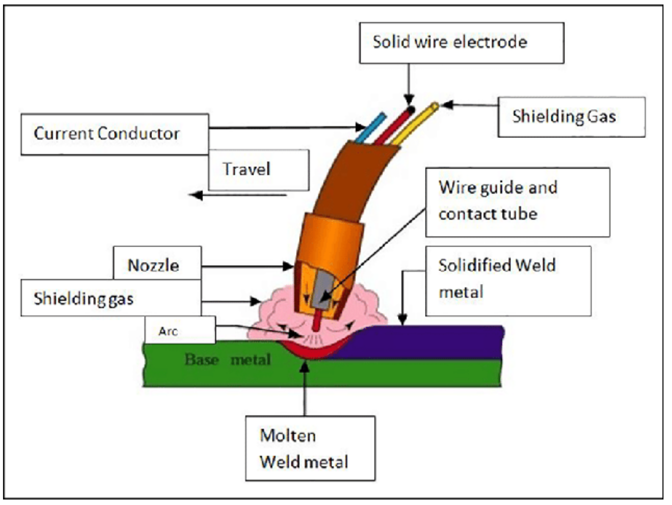


Figure 4.11 metal inert gas welding process [20]

Chemical composition of the shielding gas can affect the process of welding in several ways. For example, certain gases, such helium or argon, may provide better arc stability, resulting in a more consistent weld and less distortion. Other gases, such as carbon dioxide, may provide better penetration but can also result in higher distortion due to the higher heat input.

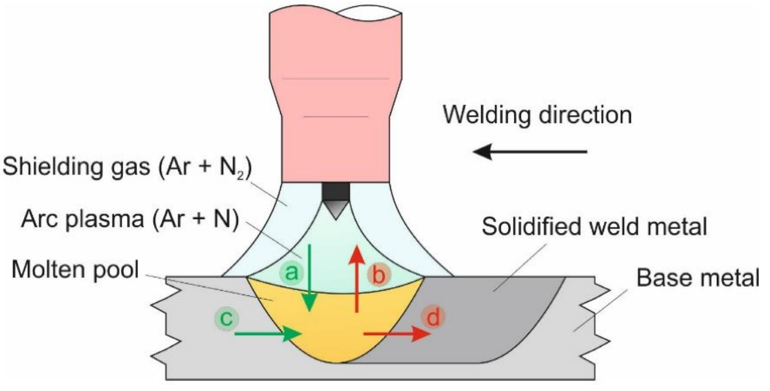


Figure 4.12 illustration of the nitrogen absorption (a,c) and desorption (b,d) along autogenous tungsten inert gas (TIG) welding [21]

Aside from the chemical composition of the shielding gas, the flow velocity and direction of the gas can also influence distortion. Insufficient gas flow or improper direction can result in inadequate shielding, which can lead to oxidation and other problems that can cause distortion.

To minimize distortion during welding, it is important to carefully select the appropriate shielding gas and to use the correct flow rate and direction. Welders should be trained to monitor the gas flow and adjust it as necessary to ensure proper shielding and to minimize distortion during the welding process.

4.2.2.4 Gas flow rate

Gas flow rate is a distortion parameter in welding, especially in techniques that utilise shielding gas, such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) [22].

In GMAW, for example, the gas flow rate influences the distribution of shielding gas over the weld region, which in turn influences weld penetration and weld quality. A high flow rate can generate excessive turbulence and gas flow disruptions, which can reduce weld quality, whereas a low flow rate can cause inadequate shielding and a higher risk of oxidation or contamination of the weld.

Similarly, in GTAW, the gas flow rate can affect weld protection against air pollutants as well as weld cooling rate. A high gas flow rate can cause quick cooling, which can raise residual stresses and deformation, whereas a low gas flow rate can cause insufficient protection and an increased risk of weld porosity.

To achieve consistent quality and reduce distortion, it is critical to precisely manage the gas flow rate during welding. The appropriate gas flow rate will be determined by the welding technique, the material being welded, and the welding conditions.

Typically, 15-20 l/min for MIG welding and 6-10 l/min for TIG welding will suffice. Your welding application - manual jobs normally demand a lower flow rate, whereas automated or mechanized labor requires a higher flow rate.

Table 4.3 Gas flow rate chart [22]

MIG Gas Flow Rate Chart			
MIG Gun Nozzle Diameter	**Minimum Flow**	**Standard Flow (For Most Jobs)**	**Maximum Flow**
3/8 in. *(Small welders)*	10-15 CFH	18-22 CFH	30 CFH
1/2 in. *(Small welders)*	18 CFH	22-27 CFH	40 CFH
5/8 in. *(Industrial welders)*	22 CFH	30-35 CFH	55 CFH
3/4 in. *(Large industrial welders)*	30 CFH	30-40 CFH	65 CFH

CFH cubic feet per hour

4.2.2.5 Electrode polarity

Welding distortion can also be caused by electrode polarity, particularly in methods that use direct current (DC) and necessitate the usage of a consumable electrode, such as shielded metal arc welding (SMAW).

In SMAW, the electrode can be polarized as direct current electrode positive (DCEP) or direct current electrode negative (DCEN). DCEP, also known as reverse polarity, occurs when the electrode is linked to the welding machine's positive terminal, whereas DCEN, commonly known as straight polarity, occurs when the electrode is attached to the welding machine's negative terminal.

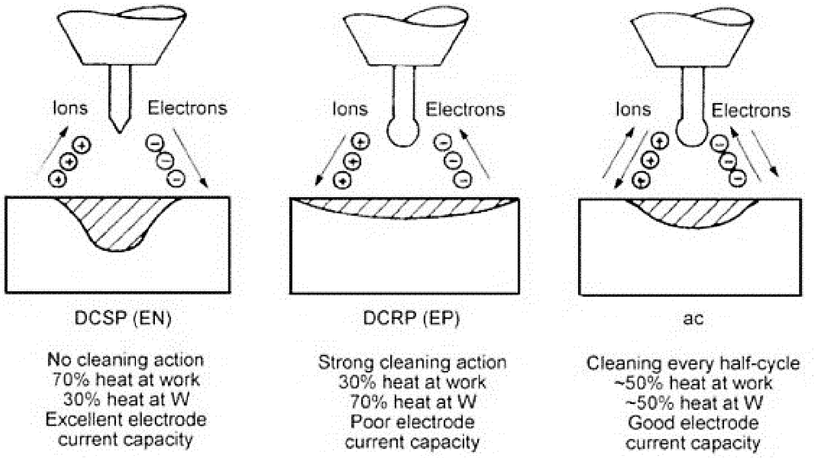


Figure 4.13 electrode polarity [23]

The choice of electrode polarity can have an effect on the weld penetration and input of the heat, which can in turn affect the distortion of the welded products. DCEP polarity typically results in deeper penetration and a higher heat input, which can lead to more distortion and a higher risk of welding defects such as cracking. DCEN polarity, will result in shallower penetration and a lower heat input, which can reduce distortion and minimize the risk of defects.

Therefore, the selection of electrode polarity should be counted by the specific welding process and the metal to be welded. It is important to consider factors such as the desired weld penetration, the required welding speed, and the risk of distortion or defects when choosing the appropriate electrode polarity.

In summary, parameters of the welding such as welding current, welding speed, welding voltage, electrode size and shape, preheat temperature, and post-weld heat treatment can all have a significant impact on welding distortions. Choosing appropriate welding parameters and implementing proper welding techniques can help minimize distortions and ensure high-quality welded joints.

4.3 Conclusions

The researchers obtained contradictory results from their trials on the gas flow rate effect and the torch angle effect. Between 50^o and 60^o torch angles, the angular distortion decreased. They also discovered that the angular distortion remained constant between 60° and 80° and increased above 80°. They also discovered that as the torch angle changed from 50° to 70°, the angular distortion increased. The angular distortion was greatest at 70° and gradually decreased as the torch angle increased. In their research, they discovered that the angular distortion decreases linearly as the torch angle increases from 70° to 100°, and that the angular distortion grew continuously as the torch angle increased from 70° to 100°.[19]

Welding speed has a negative impact on angular distortion, although wire feed rate and voltage have a beneficial impact.

The effects of shielding gas flow rate on welding angular distortion in stainless steel Tungsten Inert Gas welding were explored in a study. When the gas flow rate was increased from 5 to 15 L/min, the angular distortion decreased, and subsequently rose with higher gas flow rates. Three distinct researches discovered that the angular distortion rises as the torch angle increases. Other testing revealed that the angular distortion decreased as the torch angle increased.

The electrode weaving movement during the welding process changes the geometry of the liquid weld pool and hence the center of gravity of the weld, which impacts the angular distortion. The electrode weaving movement affects the welding distortion by determining the weld thermal stresses. There aren't enough publications that explain how electrode weaving movement affects welding angular distortion. It was discovered that the findings differed in terms of torch angle, shielding gas flow rate, and electrode weaving motion, all of which are factors influencing weld distortion. This was done to clarify the discrepancy in the key factors.

Types of cooling and welding currents are significant combinations of variables. As a result, there is a relationship between the independent and dependent variables. When excessive currents are used, fusion penetration occurs, which can lead to the collapse of the welding and an increase in the heat affected area. Shallow penetration will occur if the currents used are too tiny.

The type of fusion and reinforcement will be determined by the welding current. The increased voltage will cause the average welding width to increase, as will the width and consumption of flux. A too high voltage will destroy the welding metal's closure.

Cooling types are a significant variable in the SAW (Submerged Arc Welding) process because they determine the amount of welding and metallurgical products. The inclusion of connection fillet forms of cooling is intended to decrease the time, although at welding connections, only little blunt shorten the time. The welding time is affected by the quantity of deposit in the grooved connection. Cooling methods will reduce heat input to the welding process.

Reduced wire electrode diameter without changing other parameters raises the pressure arc, indicating deeper penetration and a wider deposit waning. The thickness of the flux layer employed in the SAW welding process determines the form and depth of the welding penetration. When the coating is too thin, the current flux is not covered, resulting in cracked outcomes. When the flux coating is excessively thick, it produces excessive reinforcement.

As a result, distortion must be controlled at all stages of production. Welding process parameters have a significant impact on welding distortions. As a result, evaluating the amount and distribution of welding distortions, as well as defining the impacts of welding conditions, can be critical. Weld current, weld voltage, and travel speed are the three most important input parameters determining welding distortion. Providing an initial angle in the negative direction is one approach for avoiding angular distortion during the fabrication process.

5 Methods to control welding distortion prior to welding

5.1 Introduction

Welding distortion that occurs during the welding process is a usual problem that can lead to poor quality welds and even structural failure in some cases. However, there are several methods that can be used to control welding distortion prior to welding. Some of these methods are:

- Welding sequence
- Welding parameters
- Preheating
- Fixturing
- Backing material
- Pre-welding fit-up

5.2 Welding sequence

Weld sequencing can also help to reduce welding distortion. This involves welding in a specific order to reduce the buildup of residual stresses. Welding in a circular or spiral pattern can also help to distribute the heat evenly and reduce distortion.

One effective strategy for reducing welding distortion is to use a weld sequencing technique. Welding sequence plays a crucial role in controlling welding distortion. Welding should be done in a specific sequence to ensure that the residual stresses generated during welding are evenly distributed. This will help to minimize distortion.

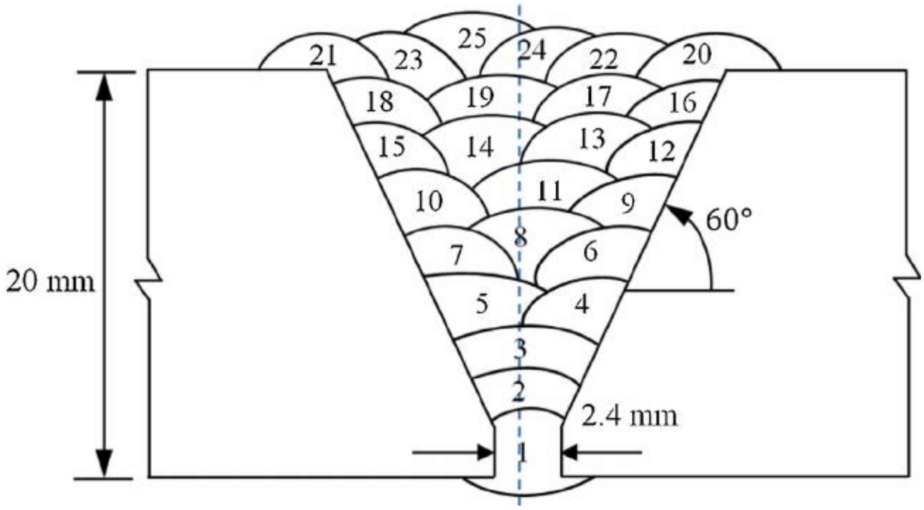


Figure 5.1 Welding sequence in bevel weld [24]

Weld sequencing involves breaking down a weld into smaller, manageable sections, which are then welded sequentially. By dividing the weld into smaller sections, the overall heat input is reduced, which helps to prevent distortion. Additionally, the use of weld sequencing can help to control the distribution of residual stresses and minimize the risk of cracking. There are several different weld sequencing methods that can be used to eliminate welding distortion, including back-stepping, skip welding, and block sequencing. Back-stepping involves welding from the center of the joint outwards, alternating both sides of the joint to ensure that the heat input is evenly distributed. Skip welding involves welding small sections of the joint, leaving gaps between the welded sections. This technique reduces the overall heat input and can help to prevent distortion.

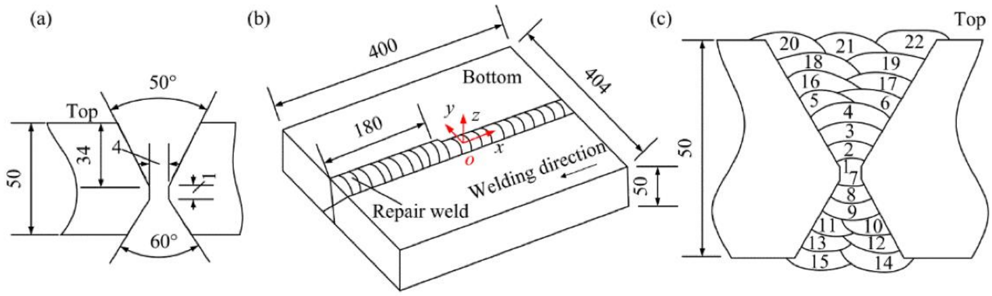


Figure 5.2 welding sequence in X weld [25]

Block sequencing involves dividing the joint into smaller blocks and welding each block separately. This approach allows for greater control over the heat input and can help to prevent distortion.

Overall, the choice of weld sequencing technique will rely on a variety of parameters, including the type of joint being welded, the welding process to be used, the materials being welded. By carefully selecting and implementing an appropriate weld sequencing strategy, it is possible to reduce welding distortion and improve the quality of the final product.

5.3 Welding parameters

Welding parameters including welding current, voltage, and travel speed can all have an impact on welding distortion. The appropriate welding parameters might help to reduce distortion.

Welding parameters like as welding speed and current can be adjusted to help reduce welding distortion. Lowering the welding current or speed can help to reduce the amount of heat input, which can lessen distortion.

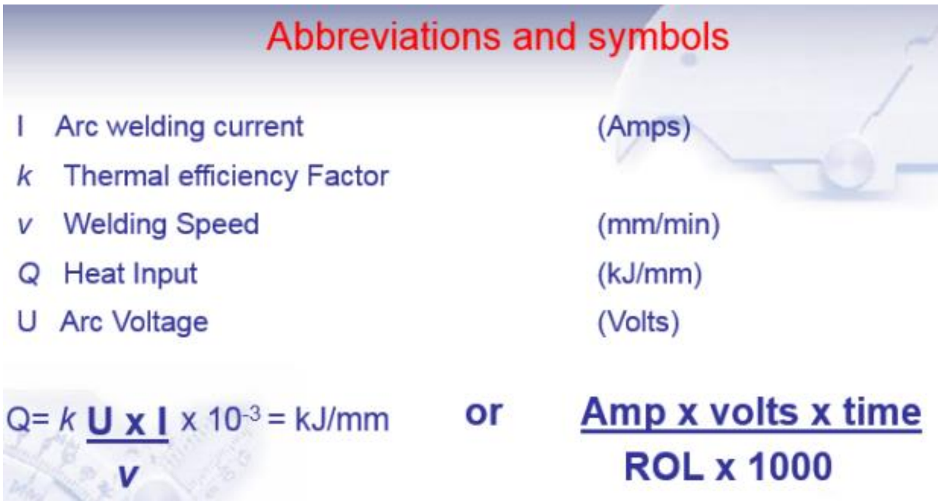


Figure 5.3 Welding parameters and thermal energy[26]

Welding distortion can be induced by a number of reasons, including the amount of heat introduced into the weld, the rate at which the weld cools, and the qualities of the materials being welded. It is critical to properly manage the welding speed and current to reduce welding distortion. Using a lower welding current and slower welding speed is one method for reducing welding distortion. Reduced heat input into the weld causes the weld to cool more slowly and undergo less shrinkage, which can assist prevent distortion. This method, however, may result in a weaker weld, so it is critical to properly balance the welding speed and current to attain the appropriate outcomes.

Another approach is to use a welding technique that focuses the heat on a smaller area of the workpiece, such as pulse welding or spot welding. By concentrating the heat in a smaller area, the amount of heat input into the workpiece can be reduced, which can help reduce distortion.

It is also important to carefully prepare the workpiece and ensure that it is properly aligned and supported during welding. This can help prevent warping and distortion caused by uneven heating or unsupported areas of the workpiece.

Overall, reducing welding distortion requires control of welding speed and current, but also attention to other factors such as welding technique and workpiece preparation.

5.4 Preheating

Preheating the workpiece before welding can also help to control distortion. Preheating is a method used to reduce welding distortion by minimizing the temperature differential on the weld zone and the surrounding base material. By preheating base material to be welded, thermal stresses that are generated during welding can be reduced, which in turn can help to minimize distortion. Preheating the base material to be welded can help to reduce thermal stresses that are caused by the welding process. This can be particularly effective for thicker sections, as they tend to cool more slowly than thinner sections.

Figure 5.4 Preheating procedure with flame in pipe welding [27]

Here are some considerations when using preheating to reduce welding distortion:

- Material type: Preheating is effective for materials with big thermal conductivity and low thermal expansion coefficients. Materials such as steel, aluminum, and copper are good candidates for preheating.
- Thickness: Preheating is most effective for thicker sections of material. As the thickness of the material increases, it becomes more difficult to dissipate the heat generated during welding, which can lead to greater distortion.
- Preheat temperature: The preheat temperature should be sufficient to reduce thermal stresses during welding, but not so high that it causes undesirable metallurgical changes in the base material. The appropriate preheat temperature will depend on the material type, thickness, and welding process being used.
- Preheat time: The length of time that the material is preheated will depend on the thickness and material type. As a general rule, thicker sections will require longer preheat times.
- Uniformity: The preheat should be applied uniformly to the entire workpiece to avoid introducing additional stresses due to uneven heating. This can be achieved by using a furnace or heating blankets to heat the entire workpiece evenly.

Figure 5.5 Preheating with electrical blankets [28]

By using preheating in conjunction with other methods such as proper fit-up and weld sequencing, welding distortion can be significantly reduced. However, it is important to ensure that the preheat temperature and time are appropriate for the material being welded, as excessive preheating can lead to undesirable metallurgical changes and compromise the quality of the weld.

5.5 Fixturing

Fixturing or clamping the workpiece in place can also help to control distortion. Fixturing can help to prevent the workpiece from moving during welding, which can lead to distortion. It involves clamping the parts to be welded in place using jigs and fixtures. This helps to reduce movement of the parts during welding, minimizing the likelihood of distortion. Fixturing the parts to be welded is an important step in the welding process. This involves securely holding the parts in place so that they remain in the correct position and alignment during the welding process. Proper fixturing is critical to achieving a high-quality weld, as it ensures that the parts are held tightly together and that there is minimal movement or distortion during the welding process.

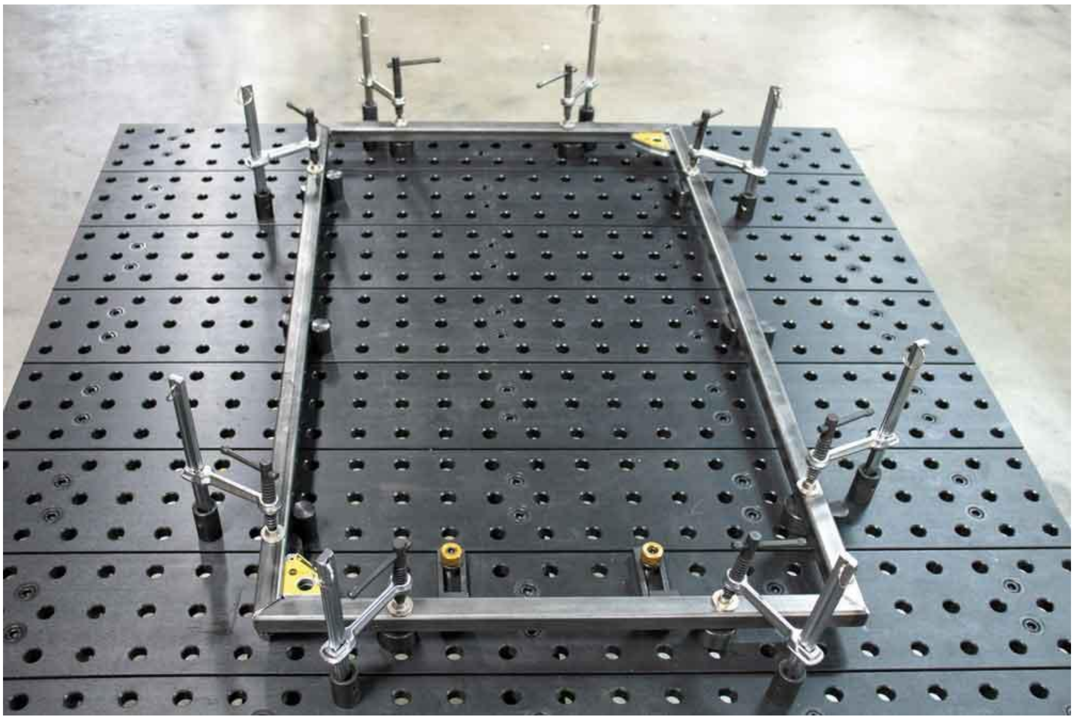


Figure 5.6 Fixturing with jigs [29]

The specific method of fixturing depends on the parts being welded, as well as the technique being used. Some common methods of fixturing include using clamps, magnets, jigs, or specialized welding fixtures designed for specific types of welding.

Regardless of the method used, it is important to ensure that the parts are securely held in place and that the fixturing does not interfere with the welding process. Proper fixturing can help to ensure that the fabricated product meets the required specifications.

5.6 Joint design

The design of the joint is also critical in controlling welding distortion. A proper joint design can help to distribute the residual stresses generated during welding evenly, which can help to minimize distortion. A joint with a high degree of restraint will tend to experience more welding distortion than a joint with lower restraint. Therefore, it may be helpful to design the joint with a lower degree of restraint where possible.

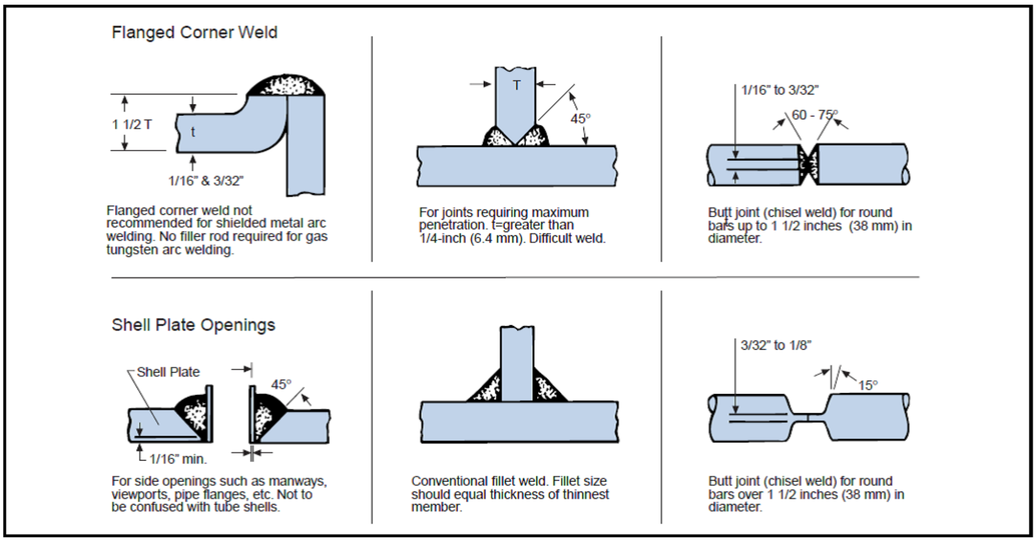


Figure 5.7a Indicational joint design [30]

Joint design is an important part of welding that involves determining the most effective way to attach two or more pieces of metal together. The joint design will be determined by a number of criteria, including the type of metal being welded, the welding process utilized, and the planned purpose of the welded product.

Butt joints, lap joints, T-joints, corner joints, and edge joints are some of the joints that can be utilized in welding. Each of these joint types has advantages and disadvantages, and the choice of a particular joint design will be determined by the unique requirements of the welding project.

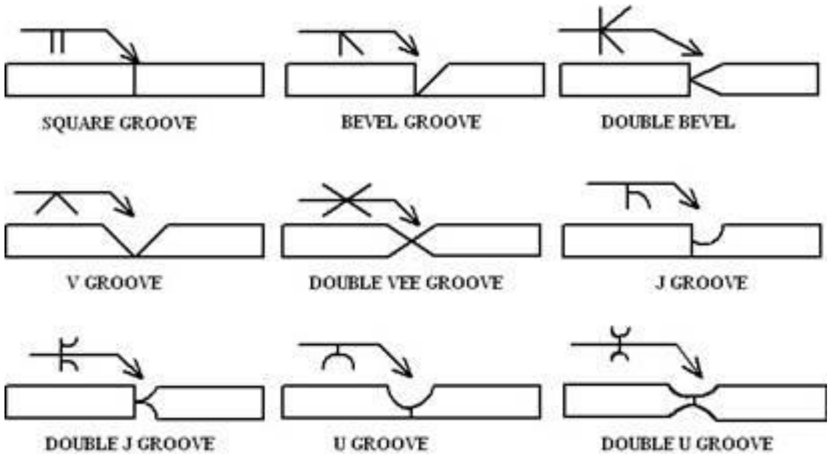


Figure 5.7b Indicational joint design [31]

Other considerations in joint design, such as the size of the weld, the position of the weld, and the type of filler material employed, must be considered in addition to the proper joint type. Proper joint design is critical to achieving a strong, durable weld that meets the required specifications.

Overall, joint design is a crucial component in the welding process, and all factors must be carefully considered when selecting the proper joint type and creating the weld.

5.7 Backing material

The backing material can also affect welding distortion. Using a backing material with similar coefficient of thermal expansion as the workpiece can help to minimize distortion. The backing material can help to dissipate the heat more evenly, reducing the likelihood of distortion.

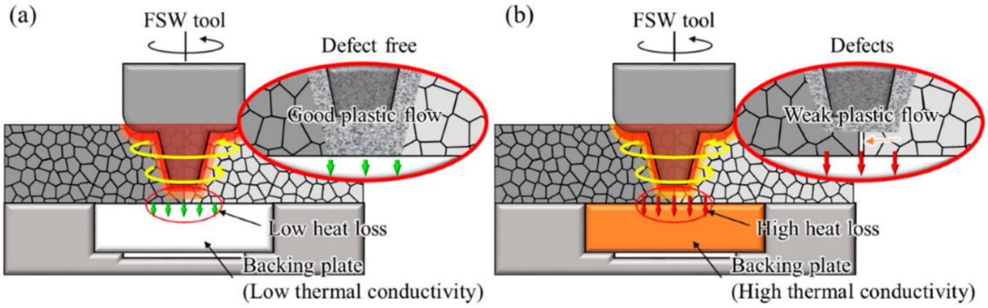


Figure 5.8 Backing material with low thermal conductivity (a) and high thermal conductivity (b) [32]

Using a suitable backing material can help control welding distortion by providing support and preventing excessive heat buildup during welding. The choice of backing material will depend on the type of welding process, the thickness and composition of the material but critically the desired final weld properties.

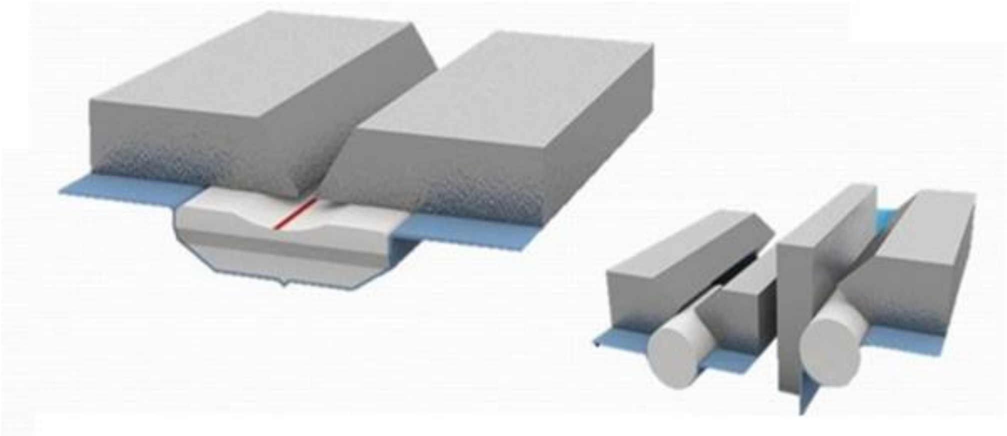


Figure 5.9a Different types of ceramic backing strips [33]

One common type of backing material is copper, which has good thermal conductivity and can help dissipate heat during welding. Copper backing can be particularly effective for welding thin materials or for methods like arc welding, processes which generate a lot of heat.

Another alternative is to utilize ceramic or glass backing, which can help protect the weld's backside from oxidation or contamination when welding. Ceramic or glass backing can be very advantageous for welding materials that are susceptible to contamination or oxidation, such as stainless steel or titanium.

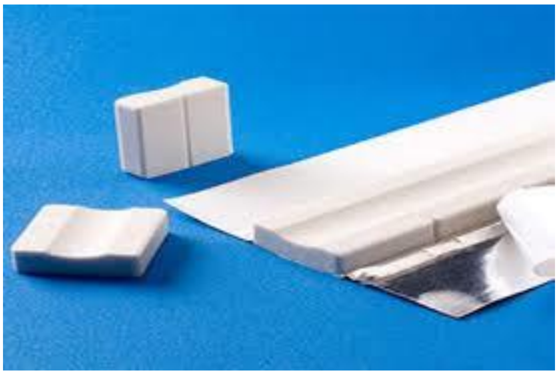


Figure 5.9b Different types of ceramic backing stripes [34]

A backing gas can be used to help control welding distortion in some instances. This entails introducing an inert gas, such as helium or argon, into the welding area, which can aid to protect the backside of the weld from oxidation and limit heat input into the workpiece.

Ultimately, choosing the backing material and technique will depend on the specific requirements of the welding project. It is significant to carefully consider factors such as heat input, material properties, and final weld properties when selecting a backing material or technique. It is important to note that welding distortion cannot always be completely eliminated, but by using these methods, it can be minimized and controlled to an acceptable level.

5.8 Pre-welding fit-up

The parts to be welded which are properly fitted up, can help reduce welding distortion. If the parts are not aligned properly before welding, it can result in angular distortion or warping of the joint during welding. Therefore, it is crucial to ensure that the parts are in the correct position before welding.

Pre-welding fit-up refers to the process of properly aligning the parts to be welded before the actual welding takes place. Proper fit-up is essential for producing high-quality welds and minimizing welding distortion.

Here are some important considerations for achieving good fit-up:

- Cleanliness: Any impurities, such as oil, grease, or rust, that can interfere with the welding process and weaken the weld, must be removed from the surfaces to be welded. Surfaces should be properly cleaned with a suitable solvent or cleaning product.
- Tolerances: The parts to be welded should be manufactured to the required tolerances. This ensures that the parts fit together properly and there is no excessive gap or overlap between the parts.
- Alignment: The parts to be welded must be aligned properly, both in terms of their position relative to each other and their orientation. Any misalignment can lead to angular distortion or warping of the joint during welding.

- Clamping: The welded parts should be securely secured in place using appropriate fittings or clamps. This prevents the pieces from moving during welding and guarantees that they remain in their proper position and alignment.
- Preparation: The edges of the parts to be welded should be prepared properly, either by machining or grinding, to ensure that they are clean and free from any defects or irregularities.

By paying close attention to these factors during pre-welding fit-up, welders can achieve good fit-up and produce high-quality welds with minimal distortion.

Overall, a combination of these methods can be used to control welding distortion prior to welding.

5.9 Conclusions

Finally, it is important to control distortion after welding for several reasons:

- Maintain the structural integrity of the welded component: Distortion in a welded component can result in changes in the shape and size of the component, which can affect its strength, stiffness, and overall performance. If the distortion is severe, it can lead to cracking, buckling, or other types of failure.
- Ensure dimensional accuracy: Distortion can also result in dimensional errors in the welded component. This can be a critical issue in parts that require tight tolerances or have to fit into other parts in an assembly.
- Avoid additional welding or machining operations: Distortion can result in the need for additional welding or machining operations in order to improve the shape and dimensions of the component after welding. These operations can be time-consuming, costly, and can introduce additional stress and heat that can further distort the component.
- Improve aesthetics: Distortion can also affect the appearance of the welded component, which can be important for parts that are visible or have an aesthetic function.

Furthermore, while the consequences of weld shrinkage may never be completely removed, you can minimize them to a minimum by taking the following practical steps:

- Reducing the volume of the metal weld to minimize overfilling and considering intermittent welding
- Reducing the number of weld runs
- Properly positioning and balancing the welds around the axis
- Using backstep or skip welding techniques, which involve laying short welds in the opposite direction
- Allowing for shrinkage by pre-setting the parts to be welded out of position
- Planning the welding sequence to ensure that shrinkages are counteracted progressively
- Shortening the welding time

Limiting distortion during cutting can be accomplished by holding the plate so that it can expand freely without buckling; ensuring the plate is flat; providing enough weld material when cutting in from corners; and utilizing a jig-saw pattern to secure the cut pieces together for multiple cutting.

When welding structural steelwork, distortion can be avoided or greatly minimized by employing anchoring devices such as strongbacks or wedges to pre-set seams in plates; flexible clamps to bring parts to the desired gap before welding; or clamps for thin sheet welding.

Longitudinal stiffeners can also be employed to prevent bowing. It is also critical to follow the proper welding sequence, such as welding the frame before the cover plate. Pre-bending or pre-setting techniques may also aid in preventing distortion, and water can be utilized to keep the operation cool.

Pipes and tubes can be distorted after welding, which can be avoided by using strongbacks attached with straps and wedges inside or outside the longitudinal joint; using backing strips to overcome transverse shrinkage or pre-setting; or welding flanges to pipes in back to back pairs. Is it possible to fix distortion? Yes, by mechanically removing the bowing with a press, shot peening, pneumatic hammering, or stress-free vibration. A sizing fixture, on the other hand, can be used to restore the distorted fabrication to its intended proportions. Different heating techniques, such as local or spot heating, can also be employed to correct distortion.

To overcome fluctuations in the heat and cold cycle during the welding process, the method of preventing and decreasing welding deformation must take into account the welding process design. The shrinkage cannot be eliminated, but it can be managed. The following are some methods for reducing shrinkage deformation.

• Avoid excessive welding.

The bigger the amount of metal in the welding site, the greater the deformation force. Setting the weld size correctly not only results in less welding deformation, but it also saves welding material and time. The amount of welding metal in the fill weld should be minimal, and the weld should be clean. It needs to be flat or slightly convex.

•Intermittent weld

Another method for lowering weld fill is to utilize more discontinuous welding, such as welding reinforcing plates. Intermittent welding can minimize weld fill by 75% while maintaining sufficient strength.

•Reduce the weld bead

Welding with thick wire and few beads causes less distortion than welding with thin wire and many beads. When there are several beads, the cumulative shrinkage caused by each bead increases the overall shrinkage of the weld, and the welding process is greater. Welding bead and fine welding rod have a better welding process impact. Pay attention to the material's heavy welding wire, less welding or thin welding wire, and multi-bead welding technique. In general, low carbon steel, 16Mn, and other materials are appropriate for thick welding wire. Weld bead welding is possible with stainless steel and high carbon steel, whereas fine wire and multi-bead welding is possible with stainless steel and high carbon steel.

- Anti-deformation technology

Bend or tilt the part in the opposite direction of the welding deformation before welding (unless for overhead or vertical welding). Experiment is required to find the fixed amount of anti-deformation. Pre-bending, pre-setting, and pre-arch welding pieces are examples of reverse welding. A simple mechanical force offset method for welding stress. When the workpiece is setup, the workpiece and welding seam flex in the opposite direction of the shrinkage stress.

The preset distortion before welding and the deformation after welding cancel each other out, resulting in a perfect plane on the welding workpiece.

Another popular way for balancing the contraction force is to clamp the same welding workpieces relative to each other. This procedure is also suitable for pre-bending. Place the wedge in the right location of the workpiece before clamping.

Due to their inherent stiffness or the mutual position of the parts, special heavy welding workpieces can generate the appropriate balance force. If these balance forces are not generated, alternative means of balancing the shrinkage force of the welding material should be applied to fulfill the goal of offsetting each other. Other contraction forces, mechanical constraint forces generated by tooling, restraint forces formed by the order of assembly and welding of the components, and gravitational restraint forces are also possible.

- Welding sequence

Determine the reasonable assembly sequence based on the structure of the workpiece, make the structure of the workpiece shrink at the same position, open the double-sided groove in the workpiece and the shaft, use multi-layer welding, and determine the double-sided welding sequence, and the fillet weld is intermittent. Shrinkage in the first welding is matched by shrinkage in the second welding. The fixture can hold the workpiece in place, increase rigidity, and reduce welding distortion. This approach is appropriate for welding small workpieces or small parts, however because of the increased welding stress, it is only appropriate for low-carbon steel constructions with good plasticity.

- Reduce welding time

Welding involves heating and cooling, and because heat transfer takes time, the time factor influences deformation. In general, it is desired that the welding would be completed as quickly as feasible before the huge workpiece is heated and expanded. The welding process, including the kind and size of the electrode, welding current, welding speed, and so on, has an impact on the welding. The degree of shrinkage and distortion of the workpiece, as well as the use of mechanized welding equipment, lowers welding time and heating-induced deformation.

Therefore, controlling distortion after welding is essential to ensure that the welded component meets the required specifications and performs as intended. Various methods can be employed to control distortion, such as pre-welding preparation, proper welding techniques, and post-welding heat treatment.

6 Methods to minimize distortions after welding

6.1 Introduction

Welding distortion is a typical issue that arises during the welding process and can have an impact on the overall quality of the weld. There are some techniques that can be used to correct distortion after welding but it is important to minimize distortions for the following reasons:

- Structural integrity: Distortion can cause changes in the shape and dimensions of welded components, which can compromise their structural integrity. Distorted parts may not fit properly or may develop cracks or other defects that can weaken the structure and minimize the load-carrying capacity.

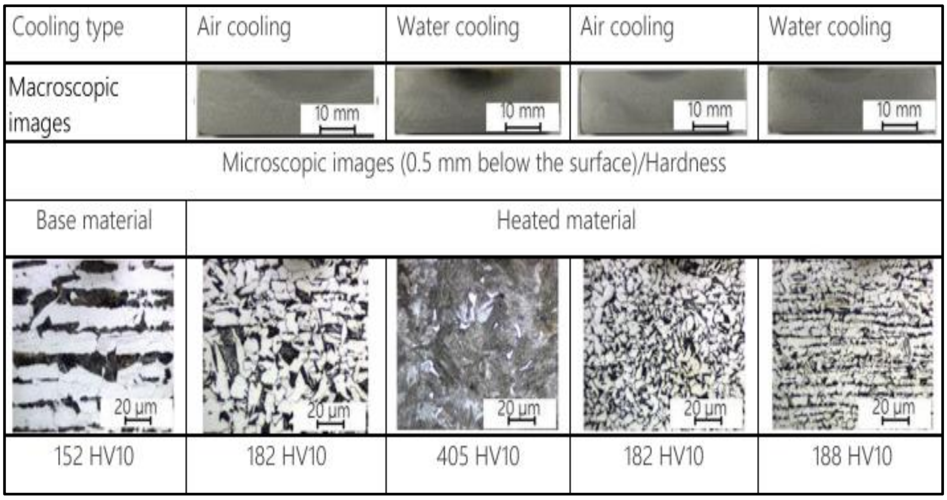


Figure 6.1 The effect in microstructure of heating on the S355J2 + N steel (t = 15 mm) [35]

- Fit and function: Distortions can affect the fit and function of welded parts. If parts are not correctly aligned or shaped after welding, they may not fit together properly, leading to operational problems or even failure of the structure. For example, if two parts are supposed to fit together with tight tolerances, distortion can cause misalignments that prevent proper functioning.
- Residual stresses: Welding can introduce residual stresses into a part, which can lead to distortion over time. Minimizing distortion after welding can help to reduce these residual stresses and ensure the long-term stability and reliability of the welded part.

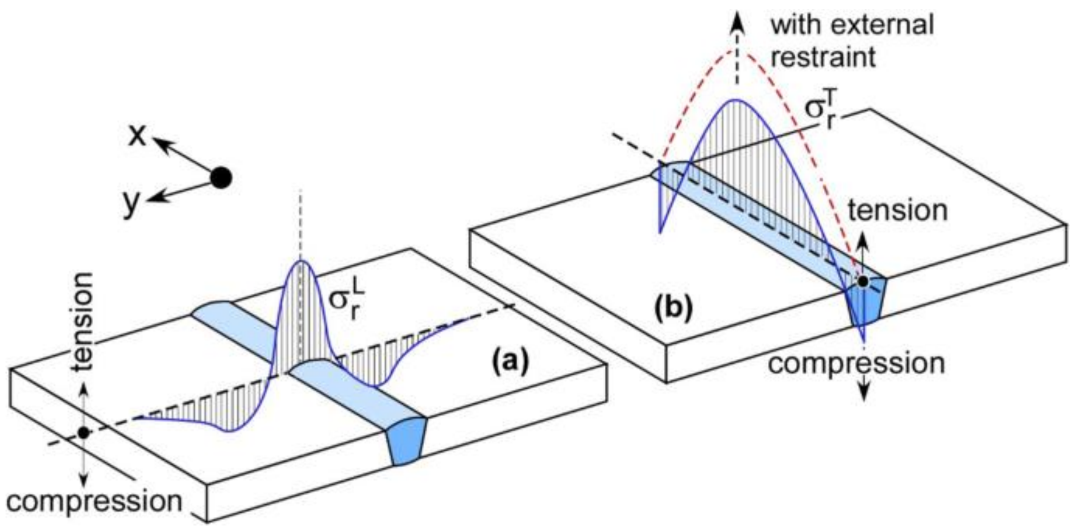


Figure 6.2 Residual stresses in butt weld [36]

- Cost and time: Correcting distortions after welding can be time-consuming and costly. By minimizing distortions during the welding process, the need for post-welding corrections can be reduced, saving time and money. Finally, minimizing distortion can save time and money by reducing the need for post-welding corrections or rework. Distortion can require additional machining, grinding, or welding to correct, which can increase the overall cost and production time. Manufacturers can increase the efficiency of the welding process and eliminate the need for costly post welding processes by avoiding distortion.
- Aesthetics: Distortions can also affect the appearance of welded parts. If a part is intended to have a specific shape or design, distortions can make it look unprofessional or unattractive. In some cases, minimizing distortion is important for aesthetic reasons. If a welded component is visible or needs to have a smooth surface finish, distortion can cause unsightly deformations or rough surfaces that detract from the appearance or reduce the performance of the part.

Overall, minimizing distortions after welding is essential to ensure that welded parts perform correctly and look good and to ensure the long-term stability and reliability of the welded structure.

Welded components frequently necessitate expensive measures to adjust for thermally induced distortions. Stresses arise in the weld as a result of volume changes, especially if the weld is limited by fixed components or other materials. These forces can cause the foundation material to shift and potentially result in tears or fractures if the constraints are partially removed. Of course, correcting distortion can be very expensive, so avoidance is essential.

6.2 Techniques to correct distortion after welding

There are several techniques that can be used to correct distortion after welding. Here are some of them:

6.2.1 Thermal Techniques -Thermal Correction

In this process, heat is applied to the distorted part using an oxyacetylene torch. The heating process, followed by natural cooling, might return the distortion to its native position. Heat is applied to the distortion on the opposite side of the weld along a straight line. Line heating can be used to correct angular distortions. Heat can be also be applied to small spots of the base metal to remove distortions on thin sheets. After welding, post-weld heat treatment comprises heating the weld and surrounding area to relieve residual tensions and minimize distortion.

Thermal stress relief (controlled heating of weldment to increased temperature followed by controlled cooling) is another way for removing shrinkage forces. Two identical weldments are sometimes secured back to back, welded, and stress-relieved while held straight. As a result, residual stresses that would otherwise distort weldments are reduced.

Localized heating is a technique used to correct distortion in specific areas of the weld. This method involves using a torch or other heat source to apply heat to the affected area and then using mechanical tools to correct the distortion while the metal is still hot.

The underlying idea behind thermal treatments is to induce sufficiently high local stresses that, when cooled, pull the component back into shape. This is accomplished by locally heating the material to a temperature where plastic deformation will occur as the hot material with lower yield strength strives to expand against the cold metal with higher yield strength surrounding it. When the heated region cools to room temperature, it will try to shrink to a smaller size than it was before heating. As a result, local heating is a simple yet efficient method of reducing welding distortion. The size, quantity, position, and temperature of the heated zones influence the level of shrinkage. Previous experience heavily influences the number and placement of heating zones. As a result, for new designs, testing will frequently be required to quantify the extent of shrinkage. Thermal distortion can be corrected using spot, line, or wedge-shaped heating techniques. However, one disadvantage of adopting thermal straightening procedures is the risk of overshrinkage or metallurgical changes caused by heating to an extremely high temperature.

It is vital to note that the success of thermal correction is dependent on the welding process utilized, the base metal used, and the precise welding parameters.

The heat applied in hot working exceeds the yield stress point. The metal is heated until molecular changes occur. When the metal reaches the right temperature, it will glow a cherry red and you will be able to move it into the desired position. Hot working, also known as thermal processing, is a method of modifying the microstructure and characteristics of a material by using heat. Hot working is frequently utilized in welding to reduce distortion in the finished welded component. Here are several ways that hot working can aid in reducing welding distortion:

You can get the metal to the desired position when it has been properly heated. It's a gamble because there's no guarantee that the metal will be restored to its previous state. Changes in molecular structure may cause additional distortions on the metal. After hot working, both the weld and the metal may develop cracks. Heat straightening is a welding rectification technique that involves applying heat to a distorted object. This permits heating, followed by a natural cooling action, to repair the deformation and return the metal to its former state. Although this procedure is not simple, welders find it quite appealing.

To accomplish heat straightening, the welder should consistently apply measured heat to the metal and allow it to expand and contract. The heating effect will direct you to alter the position and quantity of heat supplied to improve the process. It is critical to prevent raising the temperature above the point when molecular changes may occur. Remember that the goal of heating is not to alter the metal. You are heating it so that it can expand before cooling it. When heating and natural cooling are used correctly, it is simple to correct the distortion and return the metal to its original shape. One thing about this process is that it may never return the weld metal as it was before. All it does is reduce the distortion shape devoid of affecting its structural integrity or strength.

Cooling during the manufacturing process is utilized throughout the welding process in some welding methods, such as gas metal arc welding (GMAW), to help control distortion. This entails chilling the workpiece with water or air while welding in order to keep the heat-affected zone from expanding too much. Overall, hot working can be a useful method of reducing welding distortion. Welding engineers can help ensure that their welded components are dimensionally stable and free of distortion by employing procedures.

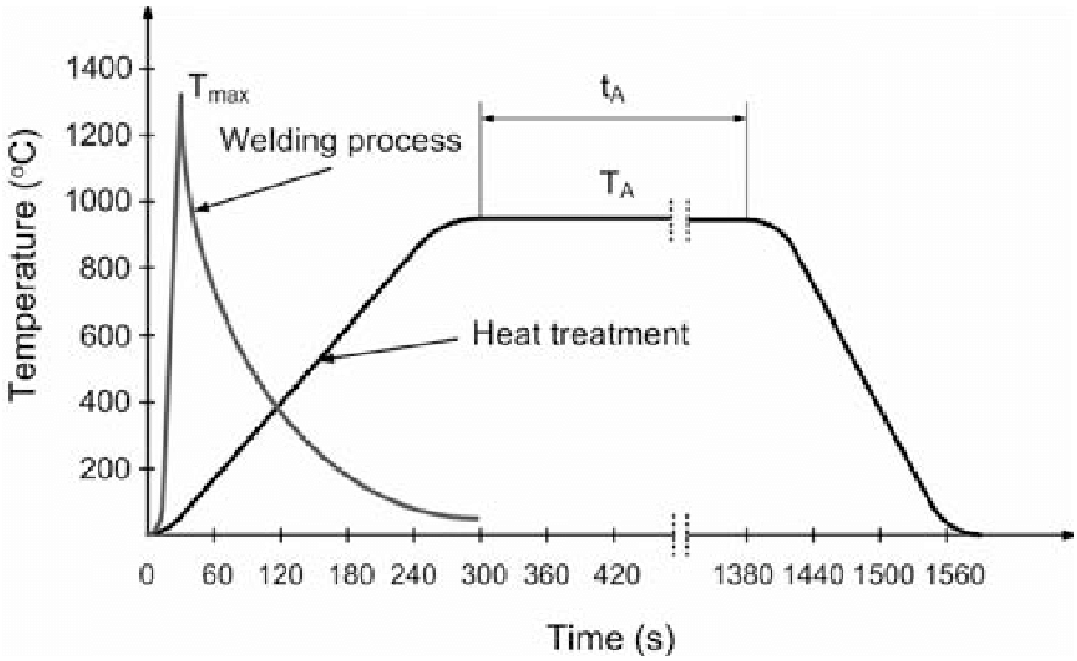


Figure 6.3 Welding thermal cycle compared with traditional heat treatment cycle: TA-austenitisation temperature, tA-austenitisation time [37]

6.2.2 Mechanical Techniques

Hammering and pressing are the primary mechanical procedures for correcting distortion. Hammering can create surface damage and work-hardening, which can lead to other issues such as decreased durability due to stress flaws or altered structural performance. When a component has bending or angular distortion, it can typically be straightened using a press without the disadvantages of hammering. Packing-pieces are placed between the component and the press platens. It is critical to apply enough deformation to cause over-correction so that the typical elastic spring-back allows the component to return to its original shape following the repair procedure.

In addition, buckles and creases, as well as other distortions, may occur during hot mechanical straightening. Pushing the metal beyond the yield stress level may result in changes to the interior metal structure.

Mechanical techniques commonly used:

- Mechanical straightening: The technique involves using hydraulic presses or other mechanical devices to apply force to the distorted area and straighten it out. It may be necessary to apply force gradually and in small increments to avoid causing additional damage.
- Hammering: Hammering can be a useful technique to fix certain types of distortions, particularly in metal surfaces. However, it's important to note that hammering may not always be the best or most appropriate technique for every situation. The effectiveness of hammering to fix distortions depends on the material and the extent of the damage. In some cases, hammering can cause additional damage or create new distortions. Therefore, it's important to assess the damage carefully and consider all available techniques before deciding on the best approach.
- Machining: In some cases, it may be necessary to remove material from the distorted area using machining techniques such as milling or grinding. This can help to remove high spots and bring the part back into its original shape.

6.2.2.1 Mechanical straightening

Mechanical straightening is a process that can be used to correct welding distortion. Welding distortion occurs because of the thermal expansion and contraction of the material during the welding process, which can cause the metal to warp or bend. Mechanical straightening involves applying force to the metal in a controlled manner in order to bend it back into its original shape. This can be done using tools such as presses, jacks, or hydraulic cylinders. It is important to note that mechanical straightening should only be used as a last resort after all other methods of reducing welding distortion have been exhausted. This is because excessive force can cause further damage to the metal and weaken its structural integrity.

Prevention is always better than correction, so to minimize welding distortion, is crucial to use appropriate welding techniques, like preheating the metal, using proper welding parameters, and using clamps or fixtures to hold the metal in place during welding. This involves using mechanical force to straighten the distorted area. A press or hydraulic machine can be used to apply force to the metal until it returns to its original shape.

6.2.2.2 Hammering

Hammering is the most common technique used to fix distortions. A hammer or power hammer is used to hit the distortion into a flat surface. This can be used in conjunction with thermal techniques to rectify many types of weld distortions. This involves using a hammer to strike the distorted area repeatedly until it returns to its original shape. This technique is often used for smaller distortions.

- Welding distortion occurs when the heat generated by the welding process causes the welded material to expand and contract, resulting in shape and dimension changes. One way to counteract welding distortion is to use a technique called "hammering in."

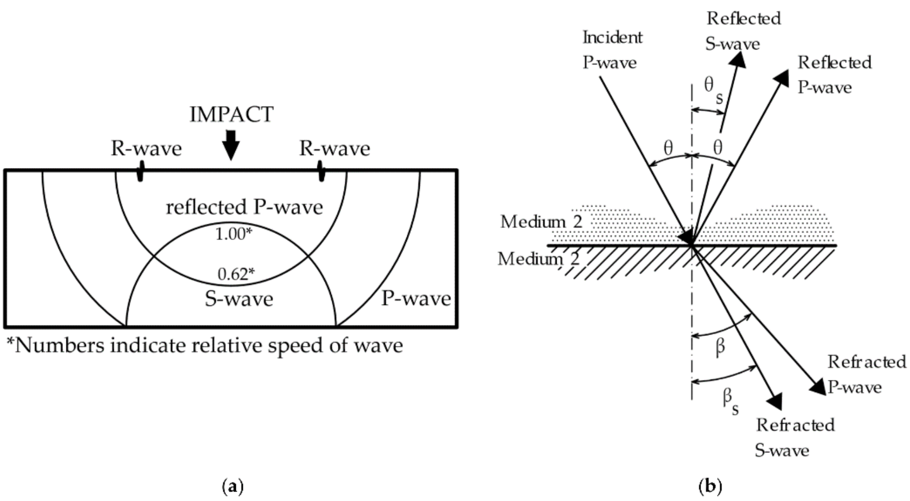


Figure 6.4 Wave theory: (**a**) Differentiation of waves during signal generation (**b**) reflection and refraction of waves at the interface of two different materials [40]

- Hammering in involves using a hammer or other suitable tool to apply force to the welded material in a specific direction, typically in the opposite direction of the distortion. This force can help to counteract effects of a welding process and bring the material back into its original shape.
- The hammering in technique is often used in combination with other techniques, such as preheating the material before welding or using clamps to hold it in place during welding. By using a combination of these techniques, it is possible to minimize welding distortion and produce high-quality welds.
- It's important to note that hammering in should be done with caution, as excessive force can cause the material to deform further or even crack. It's also important to follow

proper safety procedures when working with welding equipment and to wear appropriate protective gear, such as welding gloves and goggles.

6.2.2.3 Machining

This involves removing the distorted portion of the metal by grinding it down to its original shape. This technique can be used when the distortion is minor and localized. Grinding is a common method used to remove excess weld material and to improve the appearance and smoothness of the finished weld. However, grinding can also contribute to welding distortion if not done correctly.

Distortion is created by the uneven heating and cooling of the metal during the welding process. When the weld cools, it can contract and cause the metal to warp or bend. Grinding can contribute to this distortion by removing material from one side of the weld, which can cause it to cool unevenly.

To minimize welding distortion when grinding, it is important to follow some best practices:

- Use a consistent and light touch when grinding to avoid removing too much material from one side of the weld.
- Grind in short bursts and allow the metal to cool between each burst to prevent overheating.
- Use a low-speed grinder to reduce the heat generated during grinding.
- Use a consistent and controlled grinding pattern to prevent removing more material from one side of the weld than the other.

After grinding, allow the metal to cool slowly and naturally to reduce the risk of warping or bending. By following these best practices, you can reduce the risk of welding distortion when grinding and achieve a high-quality finished weld.

Other techniques for reducing welding distortion include pre-bending or pre-straightening the component before being welded, using clamping or featuring system to control the distortion, and using welding techniques that minimize heat input and therefore reduce residual stresses. It is important to note that the best technique to use for correcting welding distortion depends on the type and extent of the distortion. It is also important to take preventive measures to minimize the occurrence of welding distortion, such as controlling the heat input, using proper clamping and featuring techniques, and selecting appropriate welding parameters.

6.2.3 Hot Mechanical Straightening Techniques

This deformation correction process is quite similar to heat straightening. The key distinction is that the metal item is heated to the yield stress point in this method. This is the point at which the metal item begins to distort plastically. Heating metal to this temperature causes it to straighten and changes its physical appearance. You may simply change the physical appearance of the metal at this point. You can repair severe metal deformities with hot mechanical straightening. You will, however, run into some difficulties. Hot mechanical straightening is extremely unreliable. Welds and metals do fracture in some cases. It may also modify the welded metal characteristics, resulting in the occurrence, of odd situations.

It is important to note that these techniques should be used with care and should only be performed by skilled professionals. Incorrect use of these techniques can cause additional damage to the welded part and compromise its integrity.

Similar to heat straightening, but in that particular process, the material is heated near to the yield stress point. Hot mechanical straightening is a method used to correct distortion that occurs in welded components. This technique involves applying heat to the welded component and then using mechanical force to straighten it.

Furthermore, it is crucial in understanding the importance of the cause of the distortion before attempting any corrective action. If the distortion is caused by residual stresses in the material, hot mechanical straightening may only provide a temporary solution, as the stresses may reappear over time.

Therefore, it is often better in using a combination of techniques, including hot mechanical straightening, pre-bending or pre-straightening the component before welding, and post-weld heat treatment, to minimize distortion in components that are welded. Additionally, it is important to consult with a qualified welding engineer or metallurgist to determine the best approach for a particular application.

6.3 Post welded distortion reduction experimental techniques

This technique deals with welding distortion after it has been formed, hence this stage should be avoided as much as possible. However, if there has been distortion, the above procedures are useful. These solutions rely on the thermal reverse cycle to reduce distortion. It takes a significant length of time and has the potential to overheat, therefore it should be used with caution. Cozzolino demonstrated a method in which a roller moves with a specified force on the toe of a weld bead soon after welding to minimize welding distortion. He conducted two trials to evaluate distortion, the first with one roller directly on the weld bead and the second with two rollers nearby the weld bead. It has been demonstrated that rolling on top of the weld is more advantageous in reducing welding distortion because the location of the roller in the two roller ways is highly crucial to the weld bead and has a substantial impact on the result. Load on the rollers is also critical in this case to minimize welding distortion since it changes the amount of compressive stresses placed on Fig. 6.8 displays a schematic illustration of both approaches. This technique deals with welding distortion after it has been formed, hence this stage should be avoided as much as possible. [41]

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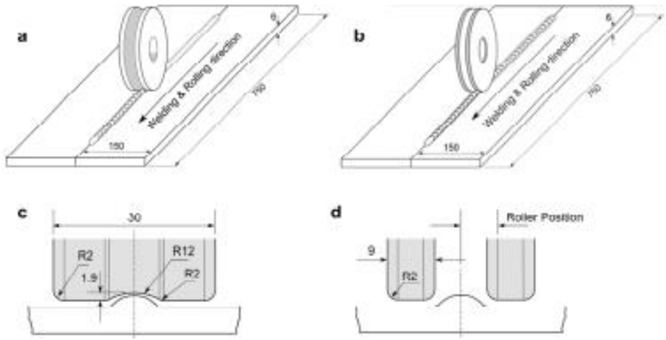

Figure 6.5 (a,c) Schematic representation of rolling on the bead (b,d) schematic representation of two rollers method [41]

According to Zhang, providing a strong temperature field after welding can lower the residual stress of the turbine bladder. If the temperature rises above 800 degrees Celsius, a corrosion fracture may form at the blade's corner. The press straightening approach may be more advantageous in butt welded pieces with no protruding components. This method can reduce the welding distortion up to zero level. To eliminate welding distortion, the LSP (Laser Shock Processing) technology is also utilized. High pulse laser shock is produced on the surface and subsurface of the weld, similar to shot penning and rolling methods. The compressive stress load is 4 to 7 times that of the shot penning method. The influence of hot peening on residual stresses on 304L stainless steel plates was represented by Hacini. It is discovered that following hot peening, there is less residual stress and deformation. Gao has demonstrated a unique Ultrasonic Impact Treatment technology on weld bead to reduce residual stress, distortion, and fatigue life of weld bead. There are numerous essential ways for controlling welding distortion, but each has a specific applicability in a certain region of processes and is dependent on the geometry of the component. Before implementing the method, research must be conducted. Many times, we had to use a variety of strategies to meet our needs. The procedures used are determined by the type of distortion. For example, angular distortion in a fillet welded vertical component can be easily controlled using the precamebring approach, however transient welding distortion techniques are necessary to control buckling distortion.

6.4 Conclusions

Limiting welding distortions after welding is also an important consideration to ensure the quality of the final product. Here are some key conclusions to keep in mind:

Heat treatment: Heat treatment can be used after welding to help relieve residual stresses that may cause distortion. The most common heat treatment methods are annealing, normalizing, and tempering.

Mechanical straightening: Mechanical straightening is a technique that involves using tools such as presses, jacks, and clamps to bend or stretch the metal back into its original shape. This method should be performed by experienced professionals to avoid causing further damage to the welded part.

Grinding: Grinding can be used to remove excess metal and smooth out rough edges that may cause distortions. However, care should be taken to ensure that the grinding does not remove too much material or weaken the weld joint.

Hammering: It involves using a hammer or other tool to strike the metal surface, which can help to relieve residual stresses and reduce distortion.

By using these techniques, welders can limit welding distortions after welding and ensure that their products meet the required specifications. It's important to note that preventing distortions during welding is the best course of action, but if they do occur, these techniques can be effective in minimizing their impact.

7 Conclusions–Suggestions for further study

7.1 Introduction

While significant research has been done on welding distortions, there is still much to be learned. Here are some suggestions for further study in welding distortions:

- Advanced Modeling Techniques: Advanced modeling techniques can help predict the distortions more accurately. This can involve the use of computer simulation and numerical methods to better understand the thermal and mechanical properties of the materials during welding.
- Material Properties: Material properties have a significant impact on welding distortions. Further examination of different materials and their mechanical properties can provide a better understanding of how to minimize welding distortions.
- Process Optimization: Welding distortions can be reduced by optimizing welding parameters. Further study on how welding parameters impact distortion and how to optimize them for specific materials and applications can help improving the quality and efficiency of welding processes.
- Welding Techniques: The study of different welding techniques and how they impact welding distortions can help to develop new and improved welding processes that are less prone to distortion.
- Welding Standards: Further research on welding standards and guidelines for preventing and minimizing welding distortions can help to establish best practices for welding professionals.

By addressing these areas of study, researchers and welding professionals can work together to better understand welding distortions and develop new techniques and processes to minimize their impact.

7.2 Advanced Modeling Techniques

Advanced modeling techniques can be used to predict welding distortions more accurately. These techniques involve the use of computer simulation and numerical methods to better understand the thermal and mechanical behavior of the materials during welding. Here are some specific modeling techniques that can be used:

- Finite Element Analysis (FEA): FEA is a numerical method that can be used to analyze the behavior of complex structures under different loads. It can be used to predict welding distortions by simulating the thermal and mechanical stresses that occur during welding.
- Computational Fluid Dynamics (CFD): CFD can be used to model the fluid flow and heat transfer that occur during welding. This can help to predict how the heat will be distributed and how the material will deform as a result.

- Phase Field Modeling: Phase field modeling is a numerical method that can be used to simulate the microstructural changes that occur during welding. This can help to predict the formation of defects such as porosity, cracks, and inclusions, which can contribute to welding distortions.
- Artificial Intelligence (AI): AI can be used to develop predictive models based on large datasets of welding parameters and resulting distortions. These models are used to improve welding parameters for specific materials and applications, reducing the occurrence of welding distortions.

By using these advanced modeling techniques, welding professionals can gain a better understanding of welding distortions and develop strategies to prevent or minimize their occurrence. However, it's important to note that modeling techniques are only as accurate as the input data used, so accurate and consistent material properties, welding parameters, and other input data are critical for accurate simulations.

7.3 Material Properties

Welding distortions are heavily influenced by material characteristics. The amount and direction of distortion can be affected by the qualities of the materials being welded. The following are some significant material features that can influence welding distortions:

- Coefficient of Thermal Expansion (CTE): The CTE shows in what grade is expansion or the contraction affected on a material with changes in temperature. Materials with a high CTE are more prone to welding distortions since they will expand more when heated during welding.
- Modulus of Elasticity: The modulus of elasticity reveals how much a material will deform under stress. Materials with a low modulus of elasticity will deform more easily under welding stresses, leading to greater distortions.
- Melting Point: The melting point of a material is the temperature at which it transitions from a solid to a liquid. Materials with a low melting point are more prone to welding distortions since they will soften or melt more easily during welding.
- Yield Strength: The yield strength of a material is the amount of stress it can withstand before permanently deforming. Materials with a low yield strength are more prone to welding distortions since they will deform more easily under welding stresses.
- Thickness: The thickness of a material can impact welding distortions. Thicker materials will require more heat to be welded, which can lead to greater distortions.

By understanding these material properties and their effects on welding distortions, welding professionals can make informed decisions when selecting materials and designing welds to minimize distortions. Additionally, advanced modeling techniques can be used to simulate the behavior of materials under welding stresses and optimize welding parameters to reduce distortions.

7.4 Process optimization

Process optimization is a critical component of reducing welding distortions. Welding parameter optimization can aid in reducing welding stresses and limiting distortion. When optimizing welding procedures to avoid distortions, keep the following points in mind:

- Welding Sequence: The sequence in which welding is performed can have a significant impact on the amount of distortion. By performing the welds in a specific order, it may be possible to limit the buildup of welding stresses and reduce distortion. Welding professionals should consider the material properties and geometry of the workpiece when determining the optimal welding sequence.
- Welding Parameters: The welding parameters, such as voltage, amperage, and welding speed, can impact welding distortion. Welding professionals should optimize these parameters to achieve the desired weld quality while minimizing welding stresses.
- Preheat and Post-Weld Heat Treatment: Prior to welding, preheating the workpiece can aid to reduce welding stresses and restrict distortion. Heat treatment after welding can also be utilized to relieve welding strains and prevent deformation. The temperature and duration of preheat and post-weld heat treatment should be carefully chosen based on the workpiece's material qualities and geometry.
- Fixturing and Clamping: Proper fixturing and clamping can help to limit the permission to move the workpiece during welding and reduce welding stresses. Welding professionals should carefully select and position fixtures and clamps to minimize distortion.
- Welding Technique: The welding technique used can also impact welding distortion. Certain techniques, such as pulsed welding or backstepping, may be more effective at reducing welding stresses and minimizing distortion.

By optimizing welding processes to minimize welding stresses and distortion, welding professionals can achieve high-quality welds with minimal post-welding adjustments or rework.

7.5 Welding Techniques

The choice of welding technique can have a significant impact on welding distortion. Here are some welding procedures that are usually used to minimize welding distortion:

- Pulsed Welding: Pulsed welding involves alternating between high and low current or voltage during welding. This technique can help to limit the amount of heat input and reduce welding stresses, which can limit distortion.
- Backstepping: Backstepping involves welding in small sections, moving backward with each pass. This technique can help to limit the buildup of welding stresses and reduce distortion.
- Tack Welding: Tack welding involves temporarily welding pieces together before performing the final weld. This technique can help to hold the workpiece in place and limit movement during welding, reducing distortion.

- Weave Welding: Weave welding involves moving the welding torch in a zigzag pattern while welding. This technique can help to distribute the heat more evenly and reduce welding stresses, which can limit distortion.
- Laser Welding: Laser welding uses a focused laser beam to weld materials together. This technique can help to limit the amount of heat input and reduce welding stresses, which can limit distortion.

By selecting the appropriate welding technique relied on the material properties and geometry of the item to be welded, welding professionals can achieve high-quality welds with minimal distortion. Additionally, advanced modeling techniques can be used to simulate the behavior of materials under different welding techniques and optimize the welding process to minimize distortion.

7.6 Welding Standards

Welding distortion is a common issue that can affect the quality and integrity of welded structures. There are several welding standards and guidelines that provide recommendations for preventing and minimizing welding distortions. Here are some of the key standards and guidelines:

- AWS D1.1: Structural Welding Code - Steel: This standard provides guidelines for welding steel structures, including recommendations for minimizing welding distortion. It recommends using a balanced welding sequence, preheating, controlling weld shrinkage, and using fixturing and jigs to prevent distortion.
- AWS D1.5: Bridge Welding Code: This standard covers the welding of steel bridges and includes provisions for controlling welding distortion. It recommends using preheat, maintaining an appropriate interpass temperature, and using fixturing and jigs to prevent distortion.
- ISO 13919-1: Welding - Electrons and laser beam welded joints - Guidance on quality level for imperfections - Part 1: Steel: This standard provides guidance on the quality level for welding imperfections in electron and laser beam welding, which can help to minimize welding distortion.
- ISO/TR 17671-1: Welding - Guidelines for the avoidance of cold cracking: This technical report provides guidelines for preventing cold cracking in welded structures, which can help to prevent distortion
- ISO 6947: Welds - Working positions - Definitions of angles of slope and rotation: This standard defines the angles of slope and rotation that should be used when welding to minimize distortion.
- ASME BPVC Section IX: Welding and Brazing Qualifications: This standard outlines the requirements for welding qualifications, including procedures for controlling distortion.

By following these standards, welders can reduce the likelihood of welding distortion and ensure that their welded structures are safe and reliable.

Welding distortion is a common issue that can affect the quality and integrity of welded structures. There are several welding standards and guidelines that provide recommendations

for preventing and minimizing welding distortions. Here are some of the key standards and guidelines:

In addition to these standards and guidelines, welders can take several steps to prevent and minimize welding distortions, such as using proper welding techniques, selecting the appropriate welding process, using proper fixturing and jigs, and controlling weld shrinkage. By following these standards and guidelines and taking appropriate measures to prevent and minimize welding distortions, welders can ensure that their welded structures are safe and reliable.

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