FCTUC FACULDADE DE CIÊNCIAS E TECNOLOGIA
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DEPARTAMENTO DE ENGENHARIA MECÂNICA

# A Critical Analysis on Weld's Distortion

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**Author**

**Filipe David Santos Cordeiro**

**Advisors**

**Dulce Maria Esteves Rodrigues**

**Carlos Miguel Almeida Leitão**

**Jury**

**President** Professora Doutora **Cristina Maria Gonçalves dos Santos**
Professora Auxiliar da Universidade de Coimbra

**Vowels** Professora Doutora **Dulce Maria Esteves Rodrigues**
Professora Auxiliar da Universidade de Coimbra

Mestre **Maria Inês Martins dos Santos Costa**
Investigadora do CEMUC

Professor Doutor **Rui Manuel Ferreira Leal**
Professor Adjunto do Instituto Politécnico de Leiria

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# Abstract

The central objective of the present thesis is to perform an extensive analysis on weld distortion, based on a literature survey containing numerical and experimental results. The mechanisms responsible for the weld distortions are explained. Several parameters that influence the weld distortion are studied, such as the structural parameters, the base material properties and the manufacturing parameters. The relations between the parameters and the weld distortion are defined based on the literature results.

Various methodologies used to prevent weld distortion as well as methods used to quantify the weld distortion are presented and described.

A study on the economic impact of weld distortion is performed.

**Keywords** Weld Distortion, Residual Stresses, Distortion Measurement, Distortion Reduction.

# Resumo

O objetivo central da presente tese é a realização de uma análise extensa sobre a distorção na soldadura, tendo como base uma revisão bibliográfica contendo resultados experimentais e de simulação numérica. São explicados os mecanismos responsáveis pela distorção. São estudados vários parâmetros que influenciam a distorção, tal como os parâmetros estruturais, as propriedades dos materiais e os parâmetros de fabrico. As relações entre os parâmetros analisados e a distorção na soldadura são definidas com base nos resultados bibliográficos

Várias metodologias usadas para prevenir a distorção na soldadura, bem como métodos usados para prevenir a distorção na soldadura são apresentados e descritos.

É efetuado um estudo do impacto económico da distorção na soldadura.

**Palavras-chave:** Distorção, Tensões Residuais, Medição da Distorção, Redução da Distorção.

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# SYMBOLOGY AND ACRONYMS

## Acronyms

FZ – Fusion Zone

HAZ – Heat Affected Zone

FSW – Friction Stir Welding

TMAZ – Thermo-Mechanically Affected Zone

SAW – Submerged Arc Welding

GMAW – Gas Metal Arc Welding

CMT – Cold Metal Transfer

# 1. INTRODUCTION

Weld distortion is defined as the warping of the component that results from the expansion and contraction of the weld material and adjacent base metal during the heating and cooling cycles associated to the welding processes. There are six types of weld distortions, as shown in *Figure 1.1*, each exhibiting its own deformation shape. The distortion's mechanisms are explained next.

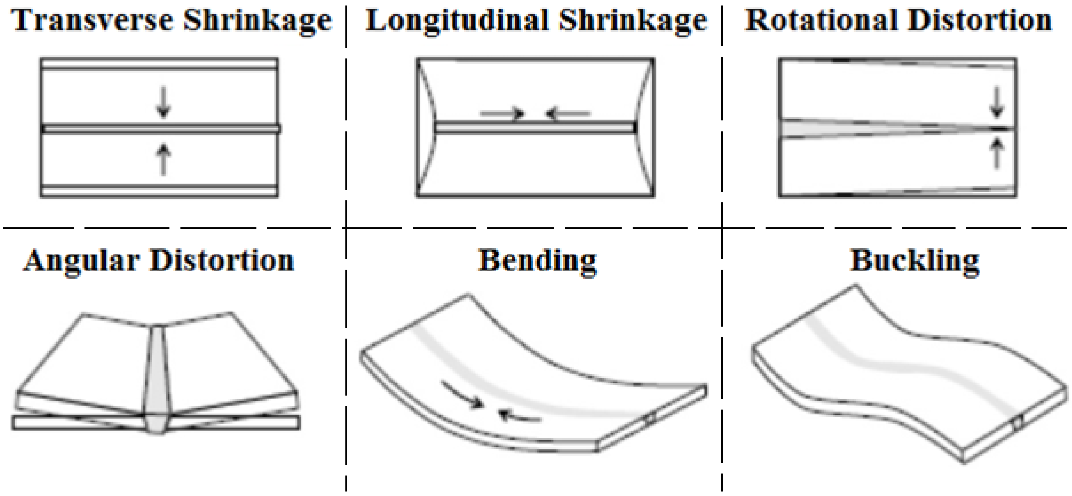


**Figure 1.1 - Different types of weld distortions. Arrows indicate the weld metal's shrinkage direction which causes the corresponding distortion.** (Soul & Hamdy 2012)

When heated, a material will expand, i.e. thermal strains occur. This expansion is proportional to the temperature change $\Delta T$ and to the coefficient of thermal expansion $\alpha$, i.e. $Thermal\ strain \propto \alpha\Delta T$ (Nebraska 2000). In fact, while welding, the heat provided to melt the weld metal, or the heat generated by friction and deformation in FSW, is not uniformly distributed in plate, generating non-linear temperature fields during both the heating and cooling stages of welding, as well as temperature gradients between the top and bottom plate's surfaces. This temperature gradients lead to non-uniform thermal expansions and thus, the non-uniform deformation in the FZ and HAZ. The residual plastic strains that remain after the thermal cycle, cause permanent deformation, i.e. weld distortion (Zhu and Chao 2002, Soul and Hamdy 2012).

The six types of distortions displayed in *Figure 1.1*, are all related to the weld shrinkage stresses. The transverse and longitudinal shrinkage types occur when the shrinkage forces are, respectively, perpendicular and parallel to the weld bead. Angular distortion occurs when the non-uniform shrinkage forces are produced through the thickness, generating a resultant force in the weld metal's centroid. When this centroid differs from the centroid of the base metal's transverse cross-section, a bending moment occurs and warps the plate (Tsai et al. 1999, Cheng et al. 2005). *Figure 1.2* shows an example of a transverse through thickness shrinkage force gradient. Bending distortion occurs for the same causes of angular distortion, yet, it is defined by both the longitudinal shrinkages and the base metal's longitudinal cross-section instead of the transversal. Rotational distortion is an in-plane angular distortion due to the localized thermal expansion and shrinkage. Lastly, buckling does not have a defined shape like the remaining types, it is nonetheless a distortion type caused by the compressive residuals stresses formed usually in the areas around the FZ (Soul and Hamdy 2012). Conrardy et al. 2006 adds that the magnitude of the buckling distortion is governed by the bending stiffness, which decreases with the presence of compressive stresses. A plate that buckles may deform into any buckling modes. Each buckling mode have a different shape (Bhide et al. 2006). *Figure 1.3* displays four buckling modes of flat plates. Several works refer the existence of a critical buckling stress of a structure (Michaleris and Debiccari 1997, Tsai et al. 1999, Deo et al. 2003, Bhide et al. 2006, Conrardy et al. 2006, Deng and Murakawa 2008). A formula to calculate the critical buckling stress of a flat plate is shown in (1.1) where $k$ is a constant, $E$ is the Young's Modulus, $v$ is the Poisson's ratio, $b$ is the plate's width and $t$ is the plate's thickness (Narayanan et al. 1999).

$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\nu^2)(b/t)^2} \tag{1.1}$$

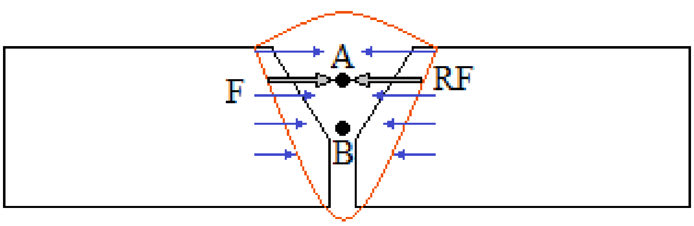


**Figure 1.2 – Development of angular distortion in butt welding of a single "V" Groove. A – Centroid of the weld metal; B – Centroid of the transversal cross-section; F – Transverse shrinkage forces (in blue); RF – Resultant shrinkage force (in gray).**

The weld stresses that generate weld distortion can be classified by three characteristics, namely; lifetime, direction and origins. In which concerns to the lifetime, weld stresses can be classified as temporary or residual. Temporary weld stresses exist only in a specific moment during the welding induced thermal cycle, while residual stresses can be defined as the stresses that remain in a material or structure after manufacture and processing in the absence of external forces or thermal gradients (Soul and Hamdy 2012).

By direction, the weld stresses can be subdivided in longitudinal or transversal weld stresses, i.e. parallel or perpendicular to the welding direction respectively. Lastly by origin, the weld stresses can be divided in thermal stresses, if resulting from plastic deformation due to temperature change, or phase transformation stresses, if caused by an increase in volume of the metal, resultant from phase transformation. (Soul and Hamdy 2012). The magnitude of the residual stresses is mainly dependent on the welding constraints and the plate’s geometry (Deo et al. 2003), while the weld shrinkage is strongly dependent on the welding heat input (Michaleris and Debiccari 1997). Both weld stresses and weld shrinkage are dependent on the welding parameters. When the heated material has its thermal expansion restricted, e.g. by colder metal areas and/or use of restraints, weld distortion is reduced and thermal stresses increase, remaining in the material after it cools ("Thermal Stresses" 2015). The evolution of longitudinal stresses during the welding is as follows: As the weld material is being deposited, the FZ is created. At high temperatures, the FZ yield strength is almost zero, i.e. the longitudinal stresses are zero. Regions surrounding the FZ exhibit temporary compressive stresses since its expansion is restrained by colder areas further away from the arc, which consequently exhibit temporary tensile stresses. When the temperature drops, the shrinkage stresses are created in the weld and surrounding areas. Shrinkage stresses are then restrained by colder adjacent areas, resulting in high magnitude tensile stresses in the weld and surrounding areas. To balance this tensile stresses, areas far away from the weld exhibit compressive stresses (Schenk et al. 2009, Soul and Hamdy 2012). Although in FSW the FZ is not created, the distribution of the residual stresses is the same as in arc welding. The tensile residual stresses appear in the TMAZ, while the areas surrounding it exhibit compressive residual stresses (Bhide et al. 2006).

The present work focus on the analysis of the factors that influence weld distortion and govern the aforementioned mechanisms, through selection and analysis of multiple articles, books, web pages and thesis. The contents of the analysed documents include either numerical simulation data, experimental data or both of them. Although experimental data gives clear and tangible results, numerical simulation has proved to produce accurate results and can cover areas where experiments are not viable, difficult to perform or hard to analyse and obtain results.

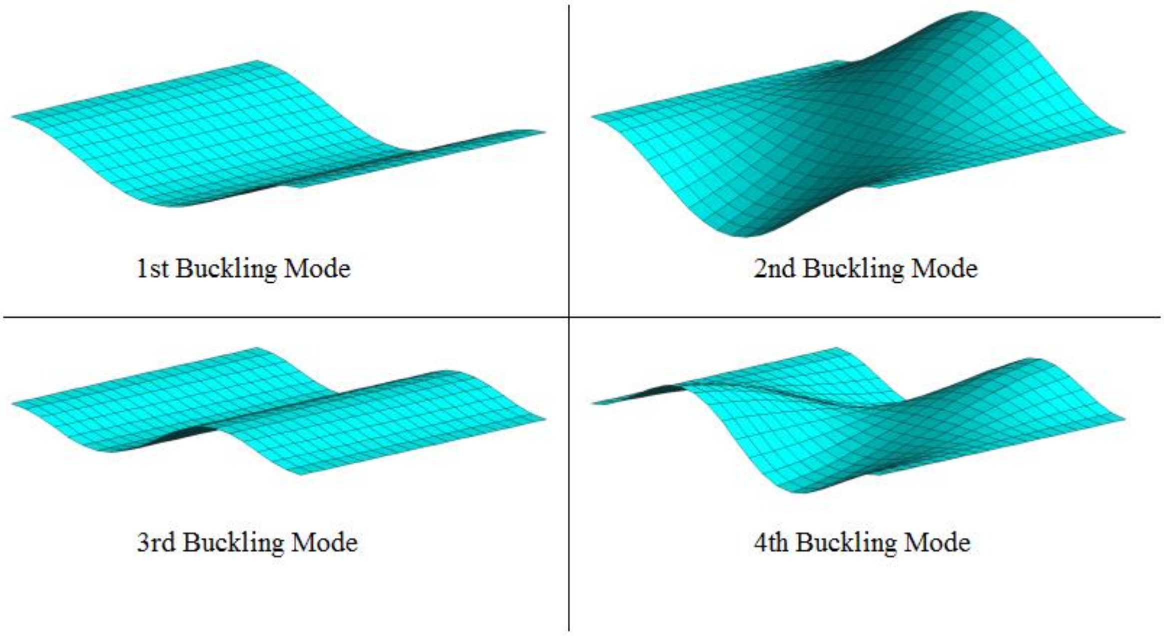


**Figure 1.3 – Image displaying the four smallest buckling modes, obtained via buckling analysis of four flat plates.** ("Linear Buckling" 2011)

# 2. WELD DISTORTION FACTORS

Weld distortion is affected by multiple mechanisms governed by factors that can be divided into three main categories: Structural Parameters, Manufacturing Parameters and Base Material Properties. Each one of these factors is individually presented and further explained below.

## 2.1. Structural Parameters

The Structural Parameters include the weld distortion mechanisms related to the plate's geometry, weld groove geometry and joint type. The influence of each of these parameters on weld distortion is herein studied for Steels and Aluminium alloys.

### 2.1.1. Geometry

The plate thickness still represents one of the highest concerns in weld distortion being therefore, one of the most analysed factors in distortion related articles. There are, nonetheless, other relevant and influential geometric parameters such as plate width, length and the presence of stiffeners. *Figure 2.1* shows seven articles where the effect of plate thickness and plate width were analysed for two different types of joints.

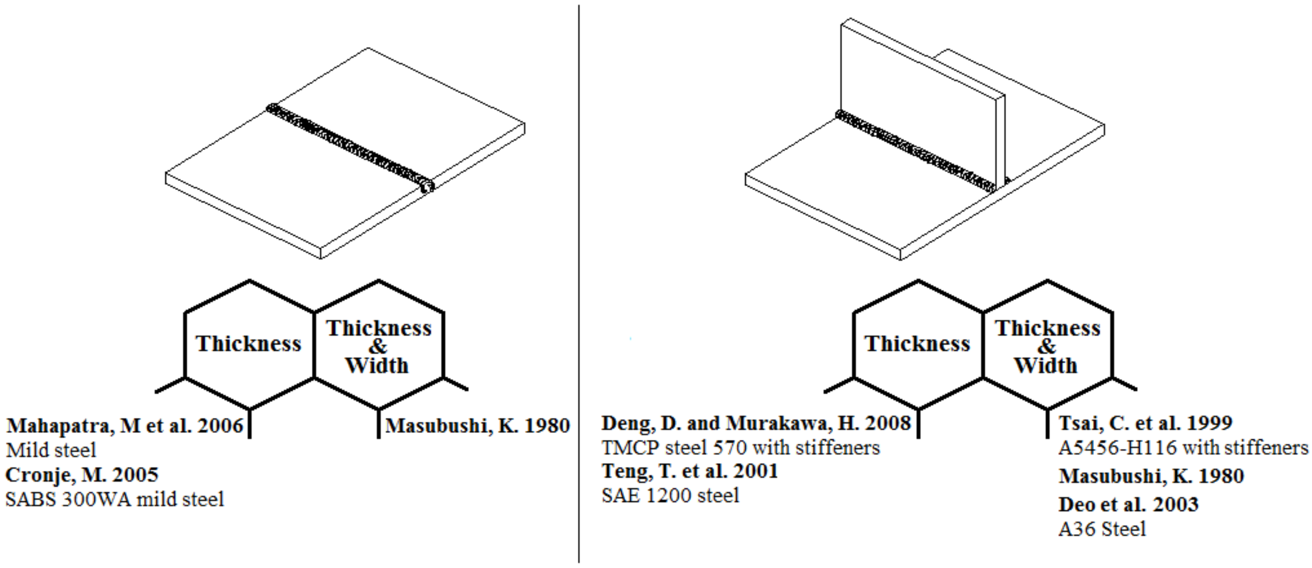


**Figure 2.1 – Diagram containing the articles read for subchapter *2.1.1* arranged by analysed factors and joint type.**

Regarding buckling and bending distortion, the quantity of results in the literature show that for a given plate thickness, the weld shrinkage force is independent of the panel width, being primarily dependent on the welding conditions. Wider panels lead to an increase of the structural rigidity and to a decrease of the residual compressive stresses around the FZ after cooling. The two aforementioned effects result in a decrease of distortion levels (Tsai et al. 1999, Deo et al. 2003). The critical buckling stress is independent of the weld shrinkage. Deo et al. 2003 concludes that critical buckling stress decreases with the increasing plate's width and length. Tsai et al. 1999 states that the bending distortion increases with the plate's length. On the other hand both agree that critical buckling stress increases with plate thickness. Such conclusions are also supported by Deng and Murakawa 2008. It is worth noting that according to the joint type and plate width there is a thickness value, referred as buckling critical thickness, bellow which, buckling distortion occurs.

In what concerns to plate thickness influence on weld distortion, there is no specific consensus between authors' conclusions. Some authors defend that using thicker plates results in a higher through thickness temperature gradient. The increased thickness also leads to an increase in structural rigidity, reducing the final weld distortion (Tsai et al. 1999, Cronje 2005, Mahapatra et al. 2006). Other authors defend that thicker plates reduce the weld metal's transverse shrinkage according to the relation $[shrinkage \propto thickness^{-2}]$ (Masubushi 1980, Deng and Murakawa 2008). However, whilst Deng and Murakawa 2008 concludes that thicker plates lead to higher angular distortions due to higher through thickness thermal gradients, a more balanced approach is present in Masubushi 1980 work stating that there is a value of thickness for which angular distortion reaches its peak in both Butt and T-fillet joint types. The latter author further explains that bellow the thicknesses peak value, there is a more uniform plate's temperature distribution, due to thermal conductivity, reducing the through thickness thermal gradients and consequent angular distortion. For thicknesses above the peak value, through thickness thermal gradient rises but the plate's structural rigidity increases and angular distortion is reduced.

Regarding residual stresses, Teng et al. 2001 concluded that thicker plates provide stronger internal restraints and increase the residual stresses.

### 2.1.2. Weld groove geometry and Joint type

Weld groove geometry has a significant influence on weld distortion as the amount of weld metal varies with both the joint type and groove angle and depth. The distance of the weld metal's centroid to the cross-section neutral axis also changes according to the groove geometry used, affecting the final distortion. Therefore, different shrinkage values can be obtained for different groove geometries. *Figure 2.2* contains eight articles that analyse the influence of the weld groove shape on weld distortion. Each article is positioned next to the respective weld groove shape analysed. The majority of articles study the weld groove shape in steels. Only Cheng's work is performed in aluminium alloys.

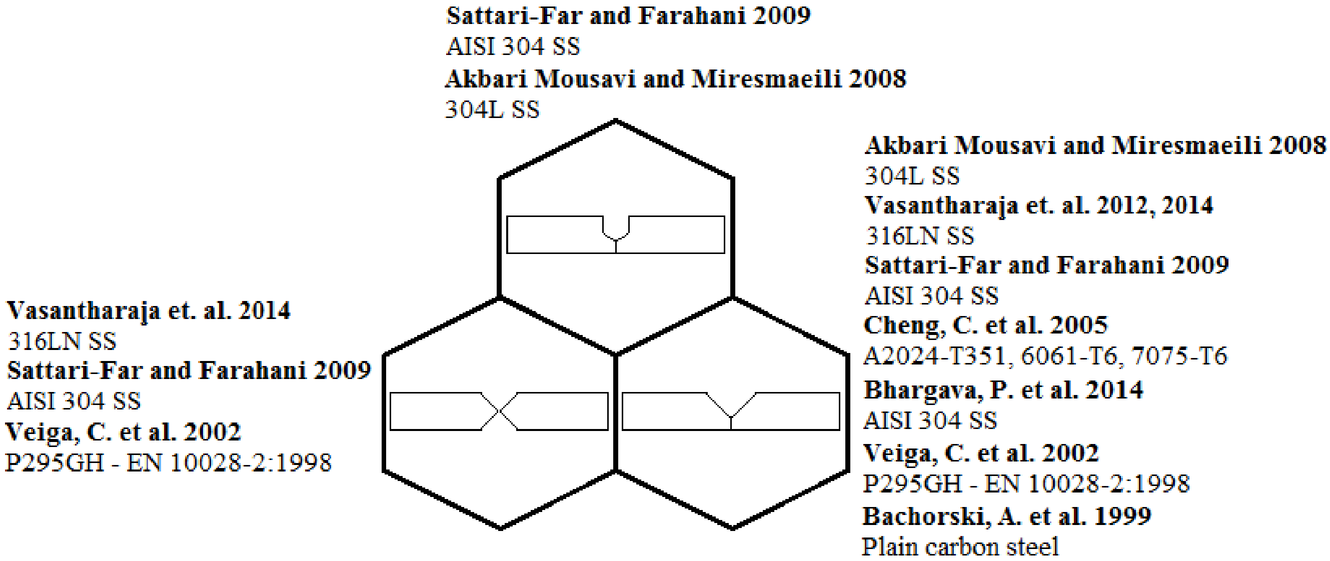


**Figure 2.2 - Diagram containing the articles read for subchapter *2.1.2* arranged by analysed weld groove shape.**

Numerical simulations concluded that the weld groove shape has an important influence on the residual stresses' distribution in thicker plates. Plates welded with a "X" groove shape, which were found to possess higher tensile residual stresses in the FZ and higher compressive residual stresses in the HAZ, show less distortions than plates welded with a "V" shaped groove (Vasantharaja et al. 2014). Plates welded with a "U" shaped groove require more weld metal than plates welded with a "V" shaped groove, however, a "U" shaped groove approaches the centroid of the weld from the neutral axis of the plate, diminishing the weld distortion (Veiga et al. 2002, Akbari Mousavi and Miresmaeili 2008, Sattari-Far and Farahani 2009). According to Veiga et al. 2002 and Sattari-Far and Farahani 2009, welding a plate with either a "V" or a "U" shaped groove produces similar results in what concerns the residual stresses. On the other hand, Akbari Mousavi and Miresmaeili 2008 conclude via experiment that a plate welded with a "U" shaped grove produce less residual stresses when compared with a plate welded with a "V" shaped groove.

Another weld groove characteristic is the preparation angle. The angular distortion was proved to increases with the V preparation angle due to the increase in the shrinkage force as a wider weld pool is formed during welding. Cheng et al. 2005 and Vasantharaja et al. 2012, agree that welding an unrestrained plate without a groove shape produces less angular distortions. Nevertheless, Cheng et al. 2005 experimental data showed that the 60º "V" shaped groove angle displays the lower angular distortion in "V" shaped weld grooves. Bachorski et al. 1999 obtained similar results, when a 50º "V" shaped grove angle was proven to display lower angular distortions than the remaining analysed angles. Experiments performed by Akbari Mousavi and Miresmaeili 2008, led to conclude that a 50º angle "V" shaped groove minimizes the residual stresses. Figure 2.3 shows the weld distortion results obtained by Cheng et al. 2005 while welding three different aluminium plates, each with three different "V" weld groove shape angles and without any weld groove shape.

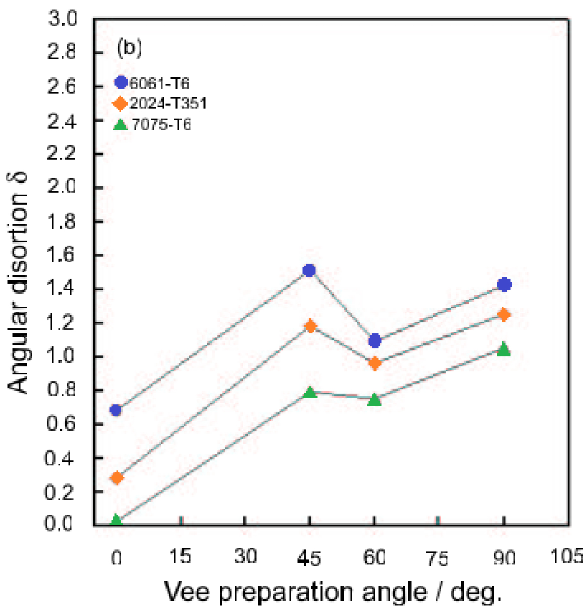


**Figure 2.3 - Angular distortion of three non-restrained aluminium alloys for four different weld groove angles.** (Cheng et al. 2005)

The last hereby analysed weld groove characteristic is the weld groove depth. By simply changing the weld groove depth, different weld bead profiles can be obtained. While keeping laser power constant, different groove depths were analysed. Typically, angular distortion increases with an increasing weld groove depth, however, there is an optimum value for which angular distortion is minimized. Weld groove depth values above and below the optimum value increase the angular distortions. Such is the result of angular distortion being a matter of balance between shrinkage force and the bending momentum lever-arm (Bhargava et al. 2014). *Figure 2.4* shows the angular distortions obtained by Bhargava with three different chamfer depths and with a flat edge.

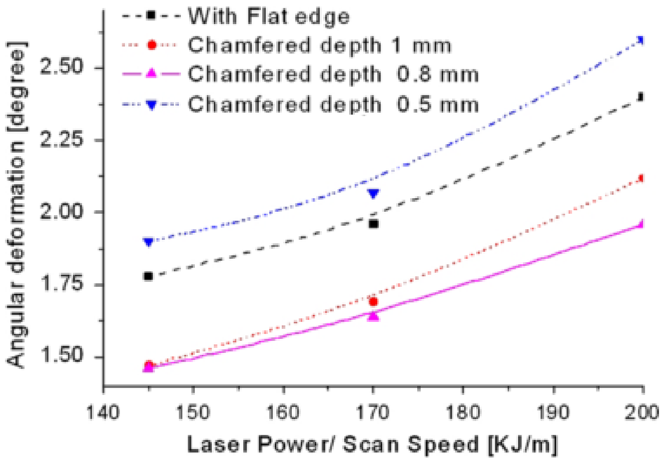


**Figure 2.4 - Graphic portraying different angular distortions obtained with various chamfer depths.** (Bhargava et al. 2014)

## 2.2. Material Properties

The mechanical and thermal properties of the base metal are of high importance in which concerns to weld distortion. The most important base metal properties which influence on weld distortion are the yield strength, the Young's Modulus, the thermal expansion coefficient, the thermal conductivity and the specific heat. Henceforth this set of properties will be referred to as thermo-mechanical properties. Figure 2.5 displays eleven articles that analyse the effect of material properties on weld distortion. The effect of base metal phase transition and the effect of thermo-mechanical properties on weld distortion is analysed for both steels and aluminium alloys.

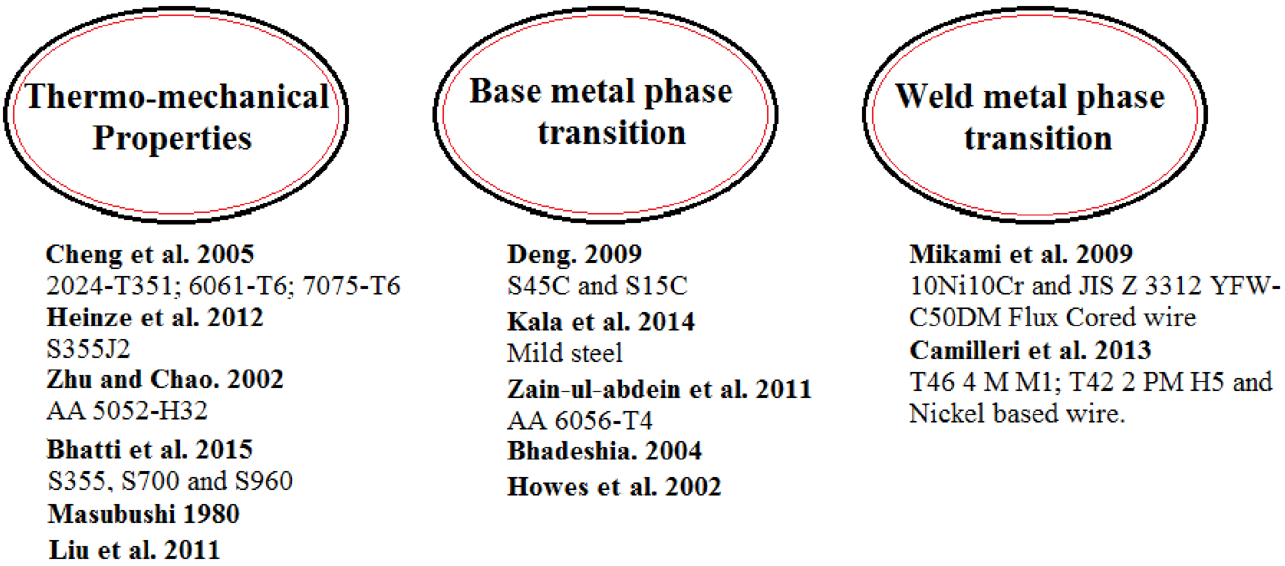


**Figure 2.5 - Diagram containing the articles analysed in subchapter *2.2,* arranged by type of analysis performed regarding material properties.**

### 2.2.1. Base Metal Thermo-mechanical properties

The Young's Modulus is linked to base material's rigidity and decreases when increasing the temperature. Furthermore, it is an integral part of the buckling critical stress (see (1.1)) (Masubushi 1980). Through different authors' analysis it can be stated that using the room temperature Young's Modulus value in numerical simulation of weld distortion, yields good results when compared to experimental data, for both steel and aluminium alloys (Masubushi 1980, Zhu and Chao 2002, Bhatti et al. 2015).

Regarding the yield strength, it decreases when the temperature increases. Using a constant value for this property in numerical simulations for both steel and aluminium simulations, not considering its temperature dependence, produces results not in conformity with the experimental test data. Thereby, if at high temperatures the yield strength is too high, there's an inability of the thermal strains to produce plastic deformations i.e. only elastic strains would be present and zero plastic strains produced. Lastly, the yield strength is considered a more important property in weld distortion for high strength steels than for mild steels. Such is due the higher distortion resistance of high strength steels when compared to mild steels. (Masubushi 1980, Zhu and Chao 2002, Bhatti et al. 2015). Experiments done with three different aluminium alloys welded with the same parameters and in the same conditions showed that the weld metal's shrinkage stresses and the weld distortions increase with the increasing base metal's yield strength at high temperatures (Cheng et al. 2005). The same results were observed when studying the angular distortion on three different steel grades (Bhatti et al. 2015).

The thermal expansion coefficient, is a property that quantifies the physical expansion of a material when heated up. The higher the thermal expansion, the higher the shrinkage stresses produced during cooldown (Masubushi 1980). The thermal expansion coefficient greatly changes from steels to aluminium alloys but has little or no variation among steel grades. In numerical simulations, both the temperature dependent thermal expansion coefficient and the room temperature thermal expansion coefficient values produce similar results close to the experimental data. This conclusion is valid for both steels and aluminium alloys ( Zhu and Chao 2002, Bhatti et al. 2015).

Concerning thermal properties, thermal conductivity and specific heat are hereby analysed. Both are known to increase slightly as temperature of the material increase. First of all, thermal conductivity quantifies the ability of materials to conduct thermal energy. Higher thermal conductivity results in a uniform heat distribution along the plate's thickness and width. With that, the thermal gradients responsible for shrinkage stresses are reduced, decreasing the weld distortion (Masubushi 1980, Liu et al. 2011). Heinze et al. 2012 numerically found that weld distortions were highly sensible to the thermal conductivity. In numerical simulations of steel and aluminium, the room temperature thermal conductivity value produces results similar to the experimental data. The thermal conductivity is considered the most important material property in the thermal analysis of aluminium alloys. (Zhu and Chao 2002, Bhatti et al. 2015).

As for specific heat, it is defined as the heat capacity per unit of mass of a certain material. The heat capacity measures the ratio between transferred heat to or from the material and its temperature change. The higher the value of the specific heat, the higher the amount of heat that has to be transferred to the material to further increase its temperature by 1ºC. Higher values of specific heat reduce the peak temperature achieved during welding (Masubushi 1980). Bhatti et al. 2015 stated that shrinkage forces are proportional to the peak temperature achieved in the plate. The specific heat is considered the most important material property in the thermal analysis of steels. The temperature dependent specific heat value should be used in order to obtain numerical simulation results close to the experimental data (Bhatti et al. 2015).

### 2.2.2. Base metal phase transition

Phase transition effect is proven to affect the residual stresses and distortions on some steel grades. Such is because the maximum temperature reached and the metal's cooling rate produce dissimilar martensitic fractions for different steel grades.

From multiple numerical simulation studies, various authors inferred that phase transformation has little effect on distortion for low carbon steels while on the other hand, it has a rather significant effect on distortion for mid and high carbon steels. It is known that when cooling rate is fast enough, the face centred cubic structured Austenite changes to a body centred tetragonal structured Martensite, increasing the material's total volume. This increase in volume partially cancels the transverse shrinkage, reducing weld distortion in mid and high carbon steels. The increase in volume creates compressive stresses in the FZ, reducing the residual stresses for mid and high carbon steels. The authors mention that the increase of volume also induces a plastic strain on the plate although none of the authors considered it in their analysis (Deng 2009, Kala et al. 2014). Various authors concluded that when the phase transformation is finished at lower temperatures, the angular distortion is lower (Howes et al. 2002, Bhadeshia 2004, Deng 2009).

According to (Zain-ul-abdein et al. 2011), for aluminium alloys, the magnitude of the distortions with and without precipitation/dissolution occurrences, expected as solid state phase transformations, are nearly the same. However, the type of distortion does change. The phase transformation in aluminium alloys also contributes to reduce the residual stresses. .

### 2.2.3. Weld metal phase transition

Distortion is also affected by the weld metal's phase transformation. Various authors concluded that using wires whose martensitic transformation starting temperatures are low, proved to decrease the angular distortion when compared with normal wires since a higher Martensite fraction is formed early on during welding. When the transformation finish temperature is achieved, the distortion's value becomes nearly constant. Through experiments there is a clear relationship between the start of the weld metal transformation's expansion and the reduction of angular distortion. When the first stops, the latter also terminates (Mikami et al. 2009).

Wires with a higher nickel percentage in their composition were experimentally proven to promote Martensite formation, however, showed no significant alteration in angular distortions' values. These wires turned out to reduce the bending distortions, owing to the reduction of the longitudinal shrinkage stresses. (Camilleri et al. 2013).

## 2.3. Manufacturing Parameters

The importance of the manufacturing parameters on weld distortion can be subdivided in Welding Parameters and Welding Procedures. The Welding Parameters include the effect on weld distortion of multiple factors such as: the electric current intensity, the electric voltage, the welding speed and the shielding gas flow. The Welding Procedures include the effects on weld distortion of three factors: the constraints, the welding sequence and the type of heat source

### 2.3.1. Welding Parameters

The longitudinal shrinkage, transverse shrinkage and weld distortion increase with the heat input. Furthermore, buckling propensity also increases with heat input (Deng 2013). However, Venkatesan et al. 2013 states the following:

> *"It is observed that, the process parameters have strong influence over bead profile and bowing distortion rather than heat input."*

Where the mentioned process parameters correspond to the aforementioned welding parameters.

Experiments performed by Venkatesan et al. 2013; 2014 and Narang et al. 2014, enabled to conclude that solely increasing the electric current intensity produces higher bending distortions. Further increasing the current intensity, means the welding speed has to be increased, in order to adapt. Such an increase of current intensity and weld speed lead to an increase in joint penetration, which counters shrinkage effects and reduces the bending distortion. However, Tian et al. 2014 only agrees with Venkatesan et al. 2013 results if welding speed is sufficiently high, stating that otherwise, for lower welding speeds, the angular distortion decreases when increasing the electric current intensity. Nevertheless, both agree that by increasing the electric current, the resulting heat input and bead width increase, hence shrinkage also increases. Noteworthy, the increase in penetration verified by Venkatesan et al. 2013 is justified by Mostafa and Khajavi 2006 who found the melting of a large volume of base metal, the reduced droplet size and their increased momentum, along with the enhanced arc force have a strong influence on penetration.

Increasing the voltage leads to a great increase in the heat input supplied to the base metal. McGlone 1978, found that a higher electric voltage also produces wider beads and taper, conducting to increased shrinkage and thus, higher bending distortion as stated by Venkatesan et al. 2013; 2014. This latter author also performed an interaction experiment between voltage and welding speed and found the results to be valid for high welding speed values. Yet once more, Tian et al. 2014 agrees with Venkatesan et al. 2013 results if weldings speed is high enough. For slow weldings speeds, Tian et al. 2014 states that an increase in voltage leads to a reduction of the bending distortion. Venkatesan et al. 2013 and Tian et al. 2014 agree that weld shrinkage increases with an electric voltage increase. Tian et al. 2014 studied a relation between electric voltage and current effects on distortion. For low electric current intensity values, an increase in voltage leads to a great amount of angular distortion. On the other hand, if the electric current intensity is high, a low electric voltage value produces high angular distortions. Increasing the voltage in this instance reduces the distortion.

In what concerns the welding speed, experiments performed by Mostafa and Khajavi 2006, Deng 2013, Venkatesan et al. 2013; 2014 and Narang et al. 2014, enabled to conclude that lower welding speeds produce high distortion and a shallow bead, with less penetration, owing to the cushion effect of the molten pool. The cushion effect occurs when the molten pool acts as a cushion to the weld metal droplets, accommodating them in the surface (Rausch 2015). On the other hand, increasing the welding speed, initially leads to a decrease in bending distortion until a minimum value is reached. At this stage, any further increase in welding speed produces higher bending distortions. Equations for angular distortion given by Pilipencko 2001 in (2.1) and Watanabe and Satoh 1961 in (2.2) confirm the results shown so far for the analysed properties. In both equations, $I$ is the electric current intensity, $U$ is the electric voltage, $v$ is the welding speed, $h$ is the plate's thickness, while $m$, $C_1$ and $C_2$ are two constants.

$$\alpha = 0.13\,\frac{IU}{vh^2} \tag{2.1}$$

$$\alpha = \left(C_1\,\frac{I}{h\sqrt{vh}}\right)^{m+1} \exp\left\{-C_2\left(\frac{I}{h\sqrt{vh}}\right)\right\} \tag{2.2}$$

Regarding the shield gas flow rate, in Venkatesan et al. 2013 experiments, increasing the $CO_2$ flow rate proved to reduce bending distortion due to the influence of gas flow rate on weld distortion, i.e. a higher gas flow implies more welding penetration. Other works, such as Banarjee 2005 state that an increase of shielding gas flow rate, and thus an increase of the number of $CO_2$ molecules, increases the heat input due to the recombination of CO with monoatomic Oxygen at the arc temperature. Therefore, a higher shielding gas flow rate produces larger weld beads. Kurihara et al. 2004 concluded that the heat input increase when increasing the shielding gas flow rate regardless of the type of shielding gas used. Lancaster 1984 observed that the shape of the weld pool is related to the type and flow rate of gas used in the arc column.

Venkatesan et al. 2013; 2014 analysed the interaction effects between gas flow rate and electric voltage and gas flow rate and electric current intensity. They found that for a high enough flow rate, by increasing voltage, bending distortion decreases. Such is explained by the increased weld penetration owing to the high gas flow rate which countered the wider bead and higher heat input effects induced by both high voltage and high gas flow rate. As for the electric current intensity interaction, by increasing the current intensity, bending distortion increases for all gas flow rates used. However, the bending distortion magnitude is lesser when using higher gas flow rates. *Figure 2.6* displays four graphics containing the bending distortion relation with electric current intensity, electric voltage, welding speed and shield gas flow rate, as obtained experimentally by Venkatesan et al. 2013; 2014.

In what concerns to arc length, Mostafa and Khajavi 2006 and Narang et al. 2014 concluded that by increasing the arc length, the welding penetration increases and weld distortion decreases. However, Narang et al. 2014 results show increased distortion for longer arc lengths. Mostafa and Khajavi 2006 also discovered that an increase in the electrode to plate angle from 90º to 120º, using Flux Cored Arc Welding and the backhand welding method, increased the welding penetration, although no further details are found on other articles to prove the validity of this statement for other welding methods.

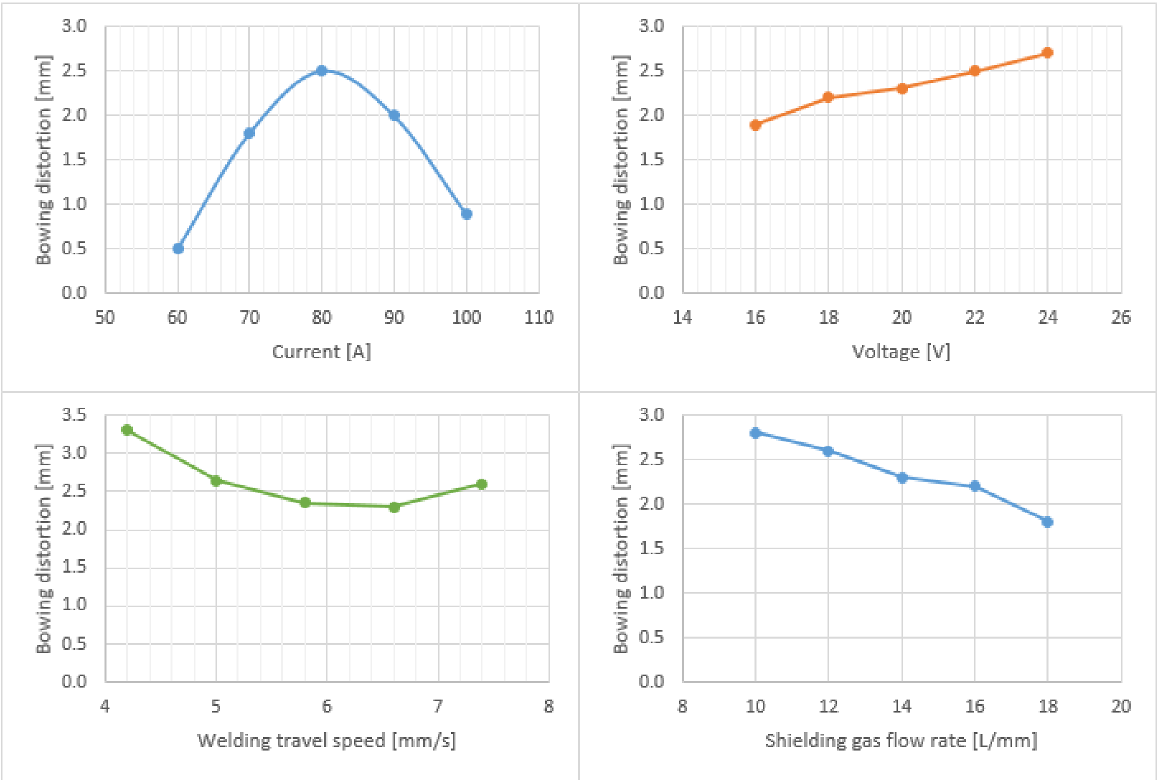


**Figure 2.6 – Direct effect on bending distortion of the 4 manufacturing parameters analysed in Venkatesan et al. 2013.**

Regarding the wire feed rate, Murugan and Gunaraj 2005 proved that the angular distortion decreases when the wire feed rate increases, until a minimum value is reached. Also, welding speed had to be adjusted accordingly as the wire feed rate increase. Such is noted since increasing the welding speed is known to decrease distortion.

### 2.3.2. Welding procedures

Number of runs and time between runs were properties studied by Murugan and Gunaraj 2005. The longer the time between runs, the higher the amount of heat lost to the plate. Such means that, if intervals are long enough, some of the heat applied to the plate, while welding the next pass, will be utilized to preheat it. Thereby, the net heat input transferred to the plate is lesser and angular distortion decreases.

In what concerns the number of runs, both the net heat input supplied to the plate and the weld distortion increase with the number of runs used. However, for a higher amount of runs, the amount of weld metal deposited starts to act as a restraint for the recent deposited pass which decreases the angular distortion per pass as the weld is built.

Three interaction studies, between the analysed factors, were performed by the Murugan and Gunaraj 2005. In all three cases, the results were in agreement with the ones obtained by modifying each parameter singularly. Nevertheless it was found that the effect of the time between runs on angular distortion is predominant over the effect of the number of runs on angular distortion. On the other hand the effect of the number of passes on angular distortion is predominant over the effect of the wire feed rate on angular distortion. Time between passes shows great effect on reducing the angular distortion when the wire feed rate is at a low value. At a higher value of wire feed rate, the angular distortion reduction provided by the increased time between passes is diminished.

Regarding the type of heat source, Colegrove et al. 2009 compared the heat input and weld distortions produced by six different welding processes: SAW, DC and Pulsed GMAW, CMT, Autogenous Laser and Hybrid Laser. Colegrove et al. 2009 welded butt-joint A131 DH36 steel grade plates. The results enabled to conclude that the plates welded with the SAW and the DC GMAW methods had the highest heat input and the highest weld distortion. The Hybrid Laser method had the lowest heat input and weld distortion. The author concludes that the Pulsed GMAW and Hybrid Laser methods produce highest quality welds with low distortion. Colegrove et al. 2009 further concluded that there is a linear relationship between Fusion Zone area and heat input.

In what concerns clamping, the usage of clamps or other form of constraints is a common technique in welding either to avoid high magnitude distortions, or to simply fix the plate while welding. The influence of clamping, number of clamps, release time and influence of clamp pre heating are hereby studied.

In articles written by Cronje 2005, Kastelic et al. 2010, Mousavi and Miresmaeili 2008 and Fu et al. 2014, it is mentioned that unrestrained weldings exhibit higher distortions but less residual stresses. A graphic representing the relation between the degree of clamping, residual stresses and distortions is shown in *Figure 2.7*. It is clear from this graphic that increasing the degree of clamping decreases the weld distortions, but increases the residual stresses. Cheng et al. 2005 and Schenk et al. 2009 stated that the large restraints provided by the clamps hinder shrinkage and produce plastic strains, in the weld zone, that relieve the residual stresses. Both Schenk et al. 2009 and Biswas et al. 2011 reported a change in weld distortion type for different number of clamps used. Nevertheless, all the mentioned authors, along with Mahapatra et al. 2006, conclude that restraining a weldment always produces less distortions. A set of images displaying the expansion and shrinkage of a restrained welded plate with the development of the plastic strains in the weld bead area is shown in *Figure 2.8*.

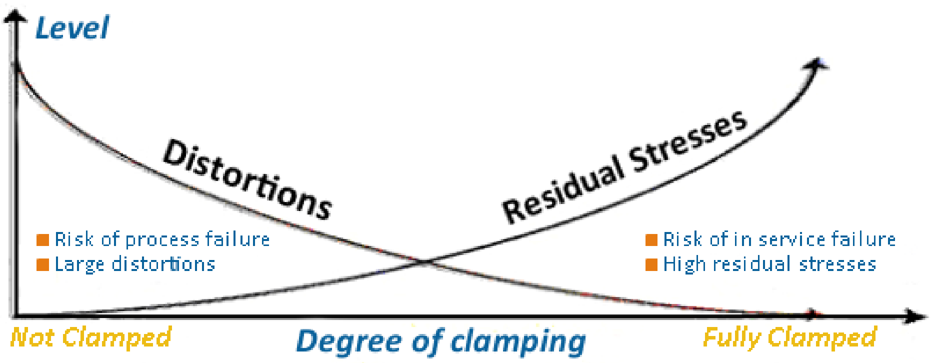


**Figure 2.7 – Version of the graphic representing the degree of clamping effect on residual stresses and on distortion made by** (Cronje 2005)**.**

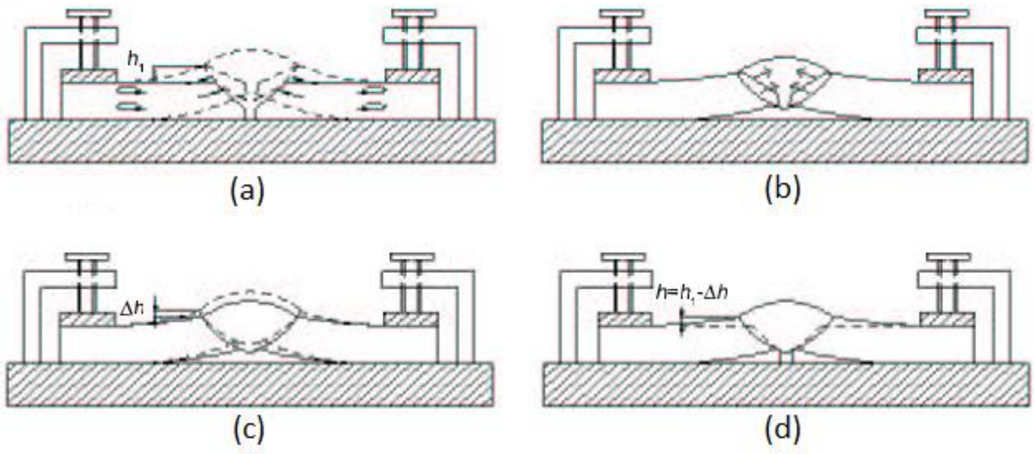


**Figure 2.8 – Development of angular distortion in restrained weldments: (a) - plastic strain (swelling) with height *$h_1$* resultant from expansion; (b) - Weld cooling and shrinkage; (c) - plastic strain *Δh* resultant from shrinkage; (d) – After weld residual plastic strain *h*.** (Cheng et al. 2005)

Regarding clamping degree:

*"The degree of restraint is a function of the type of joint, the rigidity of the structure, the amount of gap between the abutting edges and the plates' thickness."*

(Cronje 2005)

The author further explained that extreme constraining may cause failure while minimal constraining can lead to large and misaligned gaps. The reduction of distortion is not always proportional to the constraining degree, reaching a maximum when a certain number of clamps applied (Cronje 2005; Fu et al. 2014). Regarding the clamping position, Adak and Guedes Soares 2014 concluded that clamping the edges perpendicular to the weld line yields better results, producing less residual stresses, than clamping the edges parallel to the weld line. Both cases, however, produce similar distortion results.

Release time is a measure of the time elapsed between the end of the welding process and the removal of the constraints. The elapsed time has effect on both plate's distortion and residual stresses. Teng et al. 2001, Fu et al. 2014 and Guo et al. 2014 concluded that, in a restrained weld, the residual stresses could be reduced after the restraining force's release, i.e. removal of clamps. Though Cronje 2005, Ganesh et al. 2014 and Guo et al. 2014 further added that bending and/or angular distortions occurred after the removal took place, owing to the residual stresses' relieve. Schenk et al. 2009 performed a lap joint welding experiment and proved that the buckling amplitude is a function of the release time. Schenk et al. 2009 results also show that long release times, reduce the buckling amplitude, but do not prevent it from occurring. A T-fillet joint weld experiment, by the same author, showed that amplitude distortion is not affected by the clamping time, but the dominant distortion mode is. Schenk et al. 2009 subdivided the release time into three categories: hot release, where clamps are removed after welding is complete; cold release, where clamps are removed after weld's cool down; and *Transient Clamping*, where clamps are applied and /or removed as the nozzle moves, constraining only a small portion of the plate at a time.

Regarding the lap joint welded plate, the cold released plate displayed bending distortion, while the *Transient Clamping* experiment displayed buckling distortion due to the amount of compressive residual stresses formed. However, buckling distortion is triggered by compressive residual stresses (Masubushi 1980), and the use of *Transient Clamping* or cold release proved to reduce them. Regarding the hot release technique, it produces higher residual stresses than cold release (Schenk et al. 2009).

For the T-fillet joint welded plate, the hot release technique conducted to angular distortion while the cold release technique conducted to bending distortion, supressing the angular distortion almost completely. In this case, long clamping release times restrain the elastic strains from producing angular distortion but allow bending to occur. *Transient clamping* technique was found to reduce the bending distortion (Schenk et al. 2009).

The pre-heating of the clamps enables to reduce the temperature gradients in the plates, resulting in more homogenous shrinkage through the thickness as well as slower cooling rates. These two combined effects lead to a reduction of residual stresses and buckling amplitude (Schenk et al. 2009).

# 3. MANUFACTURING METHODOLOGIES DEVELOPED TO AVOID WELD DISTORTION

Various methodologies have been developed to minimize weld distortion. These methodologies include altering the design of the joints or applying restraining methods during welding to control the weld shrinkage.

## 3.1. Conventional Methodologies

A weld distortion control technique is only effective if it is appropriate for the type of distortion that is occurring in the structure being weld. Over the years, various distortion-control techniques have been developed and improved. In 2002 the Northrop Grumman Ship Systems started a program to investigate/develop distortion-control techniques associated with lightweight structures, namely for thin plate. Some of the conventional methodologies are described in the present sub-chapter. A group of 4 tables published by (Conrardy et al. 2006) containing various distortion-control techniques, their benefits and detriments are presented in the *Appendix A* of the current work.

### 3.1.1. Techniques to avoid overwelding

Performing overwelding implies more weld metal placed in the joint which increases the shrinkage stresses. Using a proper joint preparation and avoiding highly convex beads can avoid the overwelding. For thicker plates, the preparation angle can be reduced and the root opening can be increased to avoid overwelding. Other option is using an “X” or a “U” weld groove shape. *Figure 3.1* shows two examples of overwelded plates: in *a)* the bead width surpasses the weld bead theoretical throat (*T*), and in *b)* two joint preparations known to avoid overwelding are shown (Feng 2005, Conrardy et al. 2006, Lee and Beardsley 2009, “The Lincoln Electric” 2015).

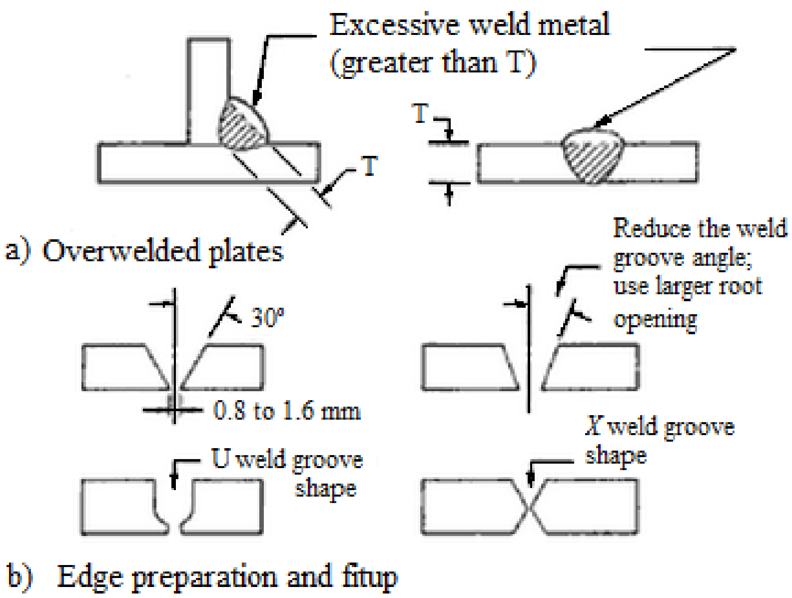


**Figure 3.1 – *a)* Overwelded plates; *b)* Common joint preparation and weld groove shapes known to avoid overwelding. ("The Lincoln Electric" 2015)**

### 3.1.2. Intermittent welding

Performing intermittent welding, as shown in *Figure 3.2*, rather than continuous welding, reduces the amount of weld metal and weld distortions. This cannot be applied to all welds. It is commonly used to weld stiffeners to plates (Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

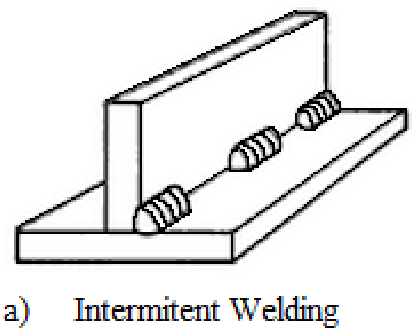


**Figure 3.2 – Example of intermittent weldings in a T-fillet joint. ("The Lincoln Electric" 2015)**

### 3.1.3. Reduce the number of passes

Reducing the number of passes, using larger electrodes or wires, produces less shrinkage stresses and angular distortion than welding in more passes with small electrodes or wires (Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

### 3.1.4. Welding near the neutral axis

This technique approaches the weld metal's centroid from the cross-section neutral axis. This reduces the lever-arm of the bending momentum and thus, the bending and angular distortions are reduced. The part *a)* of *Figure 3.3* shows two similar structures welded in two different ways. The top images displays the welds far from the neutral axis, while the bottom images display welds aligned with the neutral axis (Feng 2005, Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

### 3.1.5. Balancing the welds around the neutral axis

When welding symmetrical structures, welds should be balanced around the neutral axis. Balancing the welds around the neutral axis consists in applying the welds symmetrically around the neutral axis of the structure. With this technique, the shrinkage stresses produced by one weld, offset with the shrinkage stresses produced by other weld across the neutral axis. Owing to this, the weld distortions decrease (Feng 2005, Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015). The part *b)* of *Figure 3.3* shows two similar structures welded in different ways. The top image does not have the welds balanced around the neutral axis, while the bottom image has the welds balanced around the neutral axis.

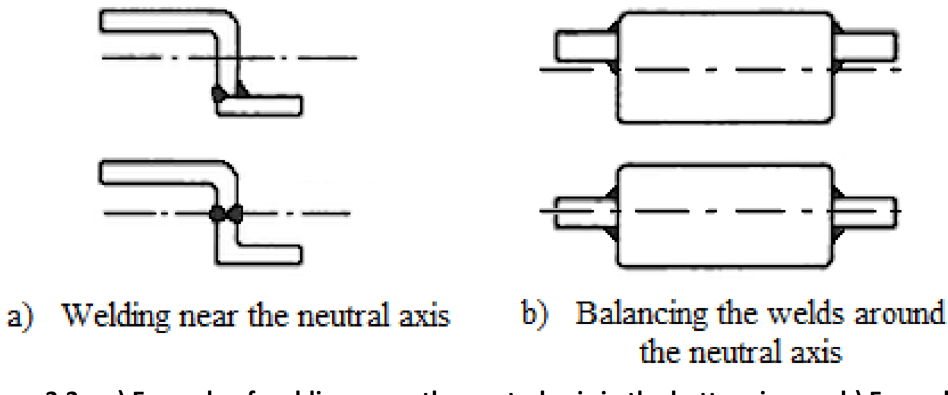


**Figure 3.3 – a) Example of weldings near the neutral axis in the bottom image; b) Example of balance of the welds around the neutral axis in the bottom image. ("The Lincoln Electric" 2015)**

### 3.1.6. Backstep welding

The *Figure 3.4* shows an example of backstep welding in a butt joint plate. The backstep technique divides a weld bead into segments and changes the welding direction of each segment. E.g. if welding from left to right, multiple bead segments are welded individually and each bead segment is deposited from right to left. This technique is not be suitable for all applications. It is not economically viable in automatic welding (Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

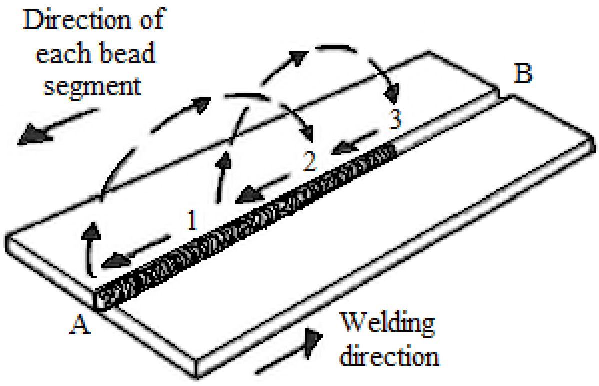


**Figure 3.4 – Example of a backstep welding. The welding direction is from point A to point B. Each weld bead segment is welded in the direction from B to A. ("The Lincoln Electric" 2015)**

### 3.1.7. Preset parts

Welding preset parts makes use of the shrinkage stresses to pull the plates into alignment to obtain plates with less weld distortion. When a specific structure is welded and the magnitude and shape of the weld distortion is previously known or predictable, preset parts can be used. Preset parts can be pre-bent, have their joint preparation changed or their clamping positions changed. *Figure 3.5* shows examples of presetting parts. In *a)* are shown parts with their joint preparation changed to offset the shrinkage stresses after weld. In *b)* are shown a convex pre-bent plate to offset the concave bending distortion (Feng 2005, Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

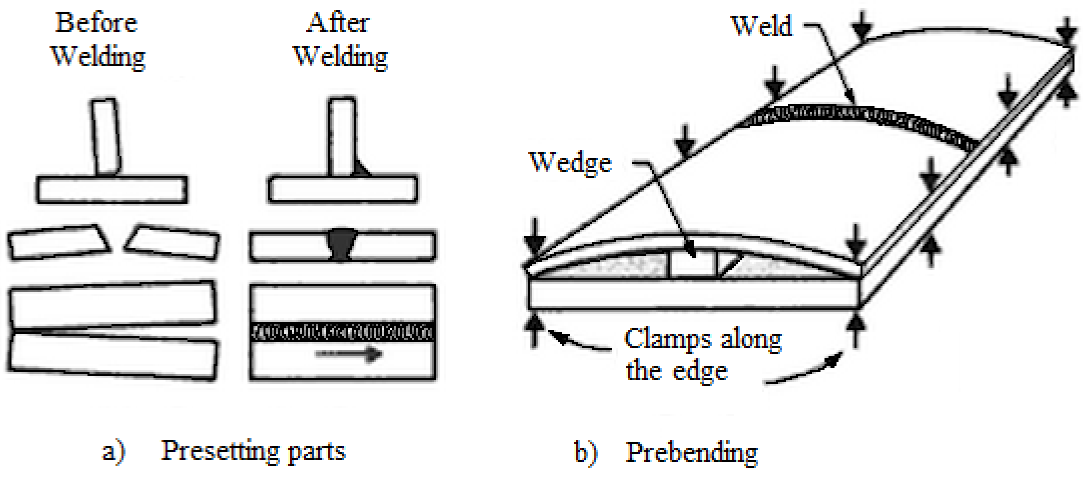


**Figure 3.5 – Presetting parts. a) Parts with joint preparation changed, before and after welding; b) Pre-bent plate after welding. The removal of the clamps will align the plate. ("The Lincoln Electric" 2015)**

### 3.1.8. Plan the Weld Sequence

Planning the weld sequence can minimize the weld distortion. Placing the weld metal alternately in different points of an assembly can make shrinkage stresses offset each other. *Figure 3.6* shows two examples of correct weld sequences that reduces weld distortions. In *a)*, the top and bottom surfaces of a "X" weld groove shape, butt-joint plate, are welded alternately. In *b)*, the left and right side of T-fillet joint are welded alternately (Feng 2005, Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

### 3.1.9. Minimize welding time

Generally, it is desirable to finish the weld quickly since time is required for heat dissipation. Longer welding times lead to the expansion of a larger volume of metal and higher distortions. Welding with automatic equipment helps reducing the welding time (Feng 2005, Conrardy et al. 2006, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

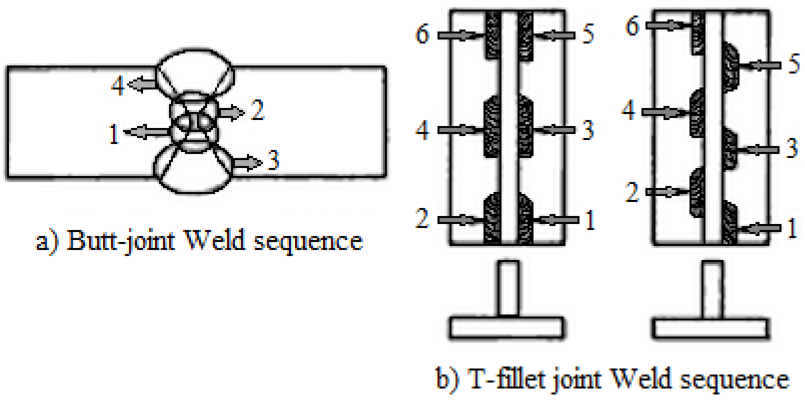


**Figure 3.6 – Examples of weld sequences that minimize weld distortion. a) Butt-joint weld sequence; b) Two T-fillet joint weld sequences. ("The Lincoln Electric" 2015)**

### 3.1.10. Reducing shrinkage stresses

When a material is cooling and the shrinkage stresses appear, using techniques to offset these shrinkage stresses helps reducing weld distortion. Peening is one of the techniques used to minimize weld distortion. Peening consists in working the surface of a metal. This can be achieved by using hammer blows or shot blasts, i.e. shot peening. Using a peening technique stretches the weld bead and makes it thinner. The induced plastic strains help relieving the tensile stresses that are formed in the weld bead as it cools. Peening also induces a higher hardness on the weld bead. This method is not normally accepted by the majority of Welding standards, specifications or codes (Feng 2005, "Peening" 2005, Lee and Beardsley 2009, "The Lincoln Electric" 2015).

Another technique to remove the shrinkage stresses is by thermal stress relieving. Thermal stress relieving consists in heating the weldments to a high temperature followed by cooling. The heating and the cooling processes are both controlled. FENG 2005

## 3.2. TRAILING HEAT SINK

The trailing heat sink technique consists in welding with a cooling nozzle attached behind the welding torch, or behind the welding tool in the case of Friction Stir Welding. The cooling nozzle releases a liquid that cools the weld bead. *Figure 3.7* displays a schematic drawing of the trailing heat sink setup during the welding process. The objective of this technique is to reduce the residual stresses to avoid buckling distortion (Gabzdyl et al. 2003, Feng 2005, Soul and Zhang 2006, Han et al. 2011, Okano et al. 2012, Soul and Hamdy 2012). Some of the liquids available to use in the cooling nozzle include liquid nitrogen (Kala et al. 2014) and liquid $CO_2$ (Richards et al. 2010).

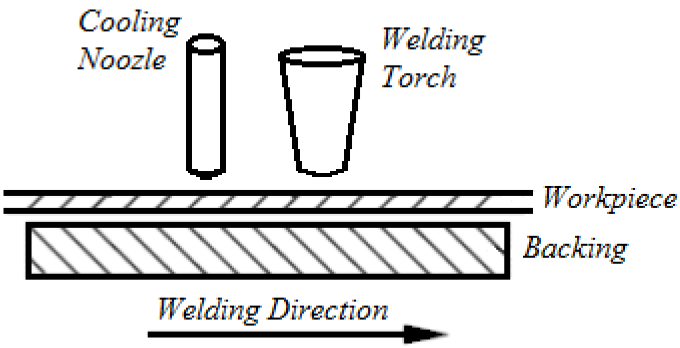


**Figure 3.7 – Schematic drawing of a trailing heat sink setup during the welding process.**

*Figure 3.8* shows eight articles that analysed the effect of the trailing heat sink on the weld distortion and residual stresses of titanium alloys, aluminium alloys and various steel grades. The welding methods used in the analysis were different.

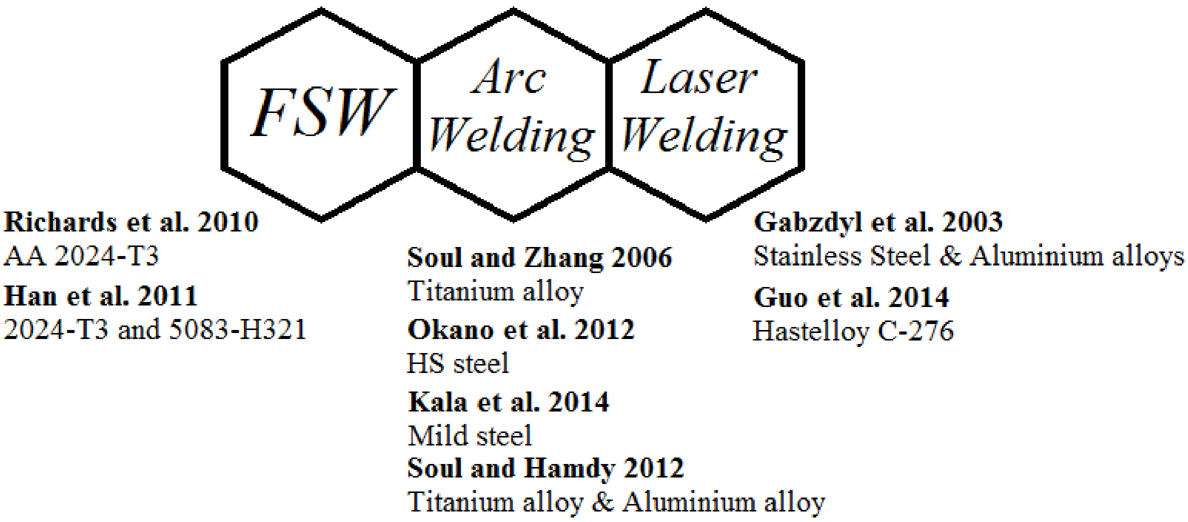


**Figure 3.8 - Articles that analysed the effect of trailing heat sink, organized by type of weld performed.**

All the authors concluded that the weld distortions are reduced when using the trailing heat sink. This technique has two other adjustable parameters which are the cooling nozzle distance to the weld bead and the cooling intensity. Richards et al. 2010 and Kala et al. 2014 concluded that the reduction of distance of the cooling nozzle from the weld bead decreases the residual stresses and weld distortion. A larger distance of the cooling nozzle from the weld bead still decreases the residual stresses but increases the weld distortions. Guo et al. 2014 concluded that residual compressive stresses and the weld distortions decrease with the increasing cooling intensity. Guo et al. 2014 further stated that compressive stresses are formed in the weld bead area.

## 3.3. Thermal Tensioning

The thermal tensioning technique can be static or transient. The static thermal tensioning consists in prestretching the weld bead area using a thermal gradient. This can be achieved by heating either side of the weld bead area while simultaneously quenching the weld bead. The transient thermal tensioning consists in welding with heating bands that travel along with the welding torch. The *Figure 3.9* displays a drawing of the transient thermal tensioning setup during the welding process. The transient thermal tensioning technique requires no quenching and provides heat to a wide area of the plate creating additional tensile zones (Feng 2005, Conrardy et al. 2006). The objective of the thermal tensioning technique is to reduce the compressive residual stresses and thus, prevent the occurrence of buckling distortion in thin plates. Michaleris et al. 1999 and Shaoqing et al. 2001 concluded that the thermal tensioning can produce structures with nearly zero residual stresses, thus no buckling distortion. Michaleris et al. 1999 further stated that when using thermal tensioning, the shrinkage values are negligible. While Shaoqing et al. 2001 concluded that transient thermal tensioning can effectively reduce bending distortion in butt-joint plates, Deo and Michaleris 2003 concluded that the same result is valid for stiffeners when welding T-fillet joints.

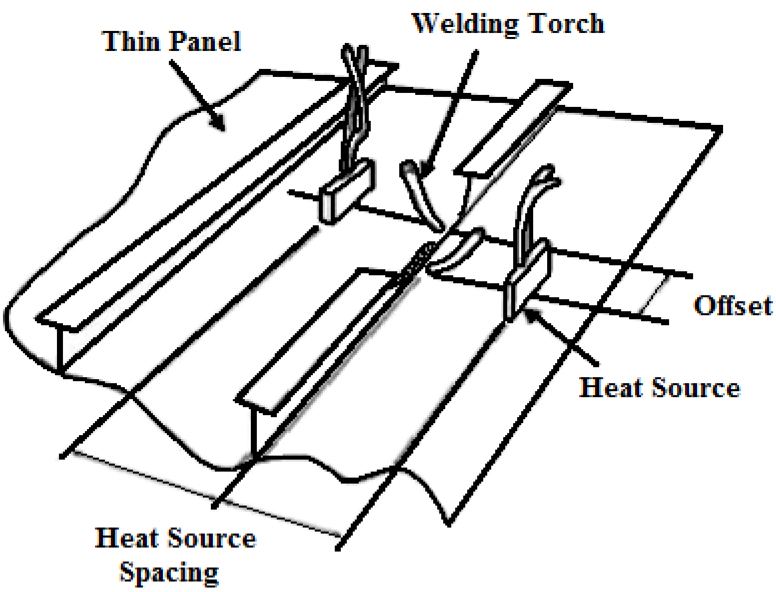


**Figure 3.9 – Drawing of a Transient Thermal Tensioning setup during the welding process.** (Conrardy et al. 2006)

# 4. METHODS TO QUANTIFY THE WELD DISTORTION

It is important to measure the weld distortion when it occurs. The instrumentation used to measure the dimensions or shape of a structure can be classified as contact or contactless, point or full-field, stationary or transient. For contact measuring methods, the instruments are normally mechanical. The contactless measuring methods include optical devices. The point measuring methods only measure the weld distortion in a single given point. On the other hand, a full-field measuring method measures the weld distortion of an entire structure. The transient measuring methods can measure the transient distortion during welding (Feng 2005).

## 4.1. Profile Tracer

The profile tracer method consists in tracing the profile of the plate on a sheet of paper. The measurement of the weld distortions are made by measuring the lines drawn in the sheet of paper. The profile tracer can be used to measure angular distortion as well as bending distortion. The profile tracer method is considered to be simple and reliable. (Venkatesan et al. 2013; 2014). *Figure 4.1* shows a schematic diagram of a profile tracer measuring bending distortion.

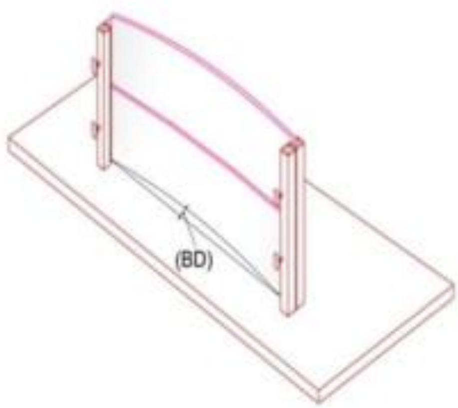


**Figure 4.1 – Schematic diagram of a profile tracer to measure Bending distortion**
(Venkatesan and Murugan 2014).

## 4.2. Dial Indicator

The dial indicator is an instrument used to measure small distances or angles. It is composed of a probe and a dial display. A dial test indicator is a dial indicator that contains a probe that swings instead of retracting. *Figure 4.2* shows a Dial test indicator commercialized by *Starrett*©. The dial test indicators can be used to measure the angular distortions ("Indicator" 2005, Pal et al. 2009, Huang 2010, Pal et al. 2010).


**Figure 4.2 - *Starrett*© B708AZ Dial Test Indicator.**

## 4.1. Vernier Instruments

### 4.1.1. Vernier Bevel Protractor

A bevel protractor consists of a circular protractor with a dial, a main scale and a beam. The graduated circular protractor is connected to a blade. The Vernier Bevel Protractor is a bevel protractor that contains a Vernier scale to provide precise readings. A representation of a Vernier Bevel Protractor and its components is shown in the left side of *Figure 4.3*. This method is used to measure angular distortions and is considered to be simple and reliable (Parmar 2003, Venkatesan and Murugan 2014, "Vernier Bevel Protractor" 2015).

### 4.1.2. Vernier Height Gauge

A Height gauge is a device used to measures the height of objects. A Vernier height gauge contains a Vernier scale for precise measurements. It is used to measure bending distortions (Parmar 2003, "Height Gauge" 2004, Murugan and Gunaraj 2005, Price et al. 2007). It is shown in the right side of *Figure 4.3* a Vernier Height Gauge commercialized by *Matutoyo*©.

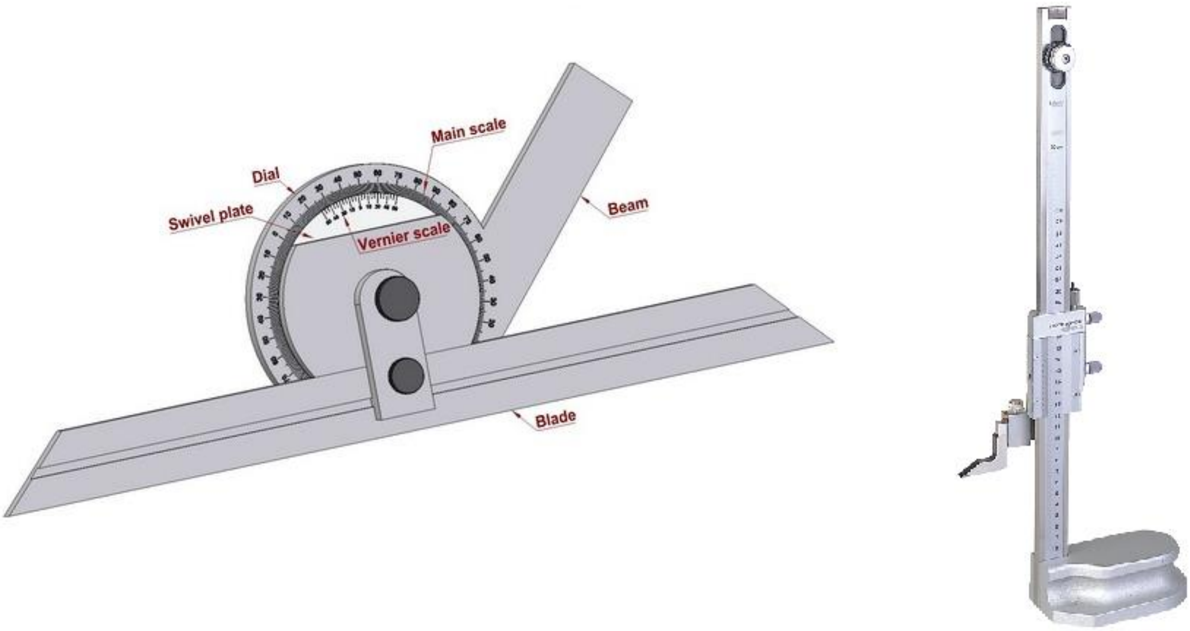


**Figure 4.3 – Left: Vernier Bevel Protractor and its constituent parts** ("Vernier Bevel Protractor" 2015)**;**
**Right: Vernier Heigh gauge S514 commercialized by *Matutoyo*©.**

## 4.2. Linear Variable Differential Transformer

This Linear variable Differential Transformer, or LVTD, is a device similar to an electric transformer that measures linear displacements by measuring the variation of the internal induced voltage. The commercial LVDT have a sensibility that varies from 0.003 to 0.25V/mm. The ranges of displacement measured with a LVTD vary from 0.125mm to 0.64mm, which can cover most of the weld distortion that occurs during welding. The LVDT can be used to measure the distortion magnitude in fixed points, during welding and cooling ("Linear Variable Differential Transformer" 2004; Feng 2005). Various experiments related in articles use this method to measure weld distortion, such as Tsirkas et al. 2003, Camilleri et al. 2005, Colegrove et al. 2009, Zain-ul-abdein et al. 2010 and Narang et al. 2014.

## 4.3. Coordinate Measuring Machines

The Coordinate Measuring Machines are used to measure the geometrical characteristics of an object. These machines can return the coordinates of any given point of an object. This devices are composed of a structure with a probe that moves in, at least, 3D. Depending on the type of probe, the measuring system can be defined as a contact scanning or contactless scanning. In contact scanning, the probe is mechanical while in the contactless scanning, the probe can be optical, laser or white light. The coordinate measuring machines are usually controlled via CNC and can be fixed or portable. This devices can be used to measure the weld distortion as well as create a 3D model of the plate if the contactless scanning system is used (Dye et al. 2001, "Coordinate Measuring Machine" 2005, Xu et al. 2007, Yu 2008, Fu et al. 2014). It is shown in *Figure 4.4* a Coordinate Measuring Machine commercialized by *Nikon*©.


**Figure 4.4 – *Nikon Altera*©, a coordinate measuring machine with a optical probe.**

## 4.4. Digital Image Correlation

The Digital Image Correlation is an optical, contactless, full-field analysis method. It is based on grey value digital images. By using two cameras, image registration techniques and a correlation algorithm, the surfaces and the contour of an object can be determined with the DIC method. The surface profiles obtained before and after welding are compared with the results in 3D deformation of the 3D object. This method requires a proper calibration of the cameras. It can be used to measure any type of transient weld distortion as well as post welding weld distortion (Chao 2005, Feng 2005, "Digital Image Correlation" 2007, "Measurement Principles of DIC" 2013). A well-known Digital Image Correlation software is *ARAMIS®*, developed by *GOM©* which also manufactures the DIC Hardware. Some articles that used Digital Image Correlation to measure weld distortion are Zain-ul-abdein et al. 2010, Perić et al. 2014. In Figure 4.5 is shown a schematic image of a Digital Image Correlation Setup with its working principle.

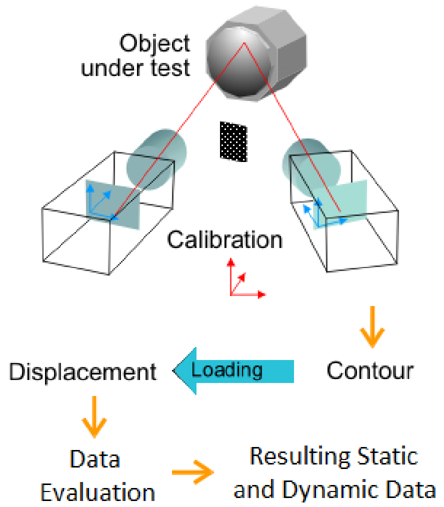


**Figure 4.5 - Schematic image of a DIC setup with the working principle ("Measurement Principles of DIC"** 2013**).**

## 4.5. Laser Scanning

Laser scanning consists in using Laser Displacement Sensors to measure the weld distortion. The sensors can be static or in movement. The sensors emit laser beams, which are reflected on the object and collected by the sensor. All information is sent to a computer to obtain the displacement values. This method allows to measure the displacements during the welding process ("Laser Scanning" 2006). It is used to measure angular, bending and buckling distortions. In *Figure 4.6* is shown a schematic diagram of a laser scanning setup used to measure weld distortion. The work performed by Conrardy et al. 2006 used LIDAR, a laser remote sensing technology to measure the distortion. Some works that used laser sensors to measure weld distortion are Camilleri et al. 2005, Mikami et al. 2009, Matsuoka et al. 2013, Guo et al. 2014 and Islam et al. 2014.

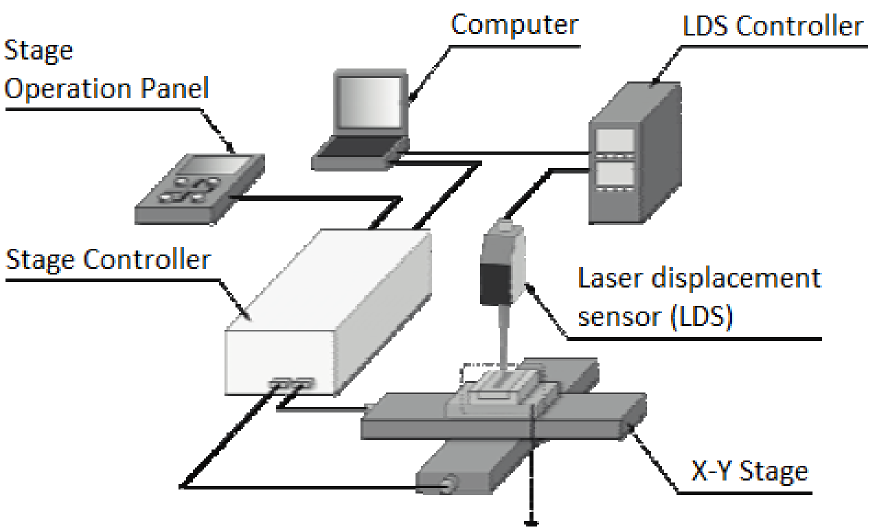


**Figure 4.6 – Schematic diagram of a laser scanning setup to measure weld distortion** (Matsuoka et al. 2013)**.**

## 4.6. Photogrammetry

The photogrammetry is a remote sensing method that makes use of photographs to get the exact position of a point or surface by using multiple point triangulation. To measure weld distortion, the most used type of photogrammetry is the close range photogrammetry. In the close range photogrammetry method, the camera is close to the object. The setup used in Photogrammetry is similar to that of the Digital Image Correlation but using photographic cameras. Photogrammetry can be used to obtain 3D models of the photographed object (Walford 2007). Experiments performed by Conrardy et al. 2006 and Lightfoot et al. 2007 used photogrammetry to measure weld distortion.

# 5. ECONOMIC IMPACT OF WELD DISTORTION IN WELDED CONSTRUCTION INDUSTRIES

The presence of weld distortion in a structure has two main problems. Firstly, it results in dimensional inaccuracies that may difficult the alignment of the edges in sub-assemblies (Camilleri et al. 2005; Deng et al. 2007). Secondly, the weld distortions increase the manufacturing costs of a structure due to additional rectifying and straightening work, which are time consuming processes, as reported by several works, such as Bachorski et al. 1999, Ghosh et al. 2010, Seyyedian Choobi et al. 2012, Wang et al. 2012, Deng et al. 2013 and Tian et al. 2014. Industries that manufacture thin plate structures like the automobile, aerospace and shipbuilding industries, display the highest rectification costs. In these industries, according to TWI, as stated by Holder et al. 2011, and Shen 2013, correcting weld distortions reach 30% of the total fabrication costs. In spite of this, in this industries, correcting weld distortion is cheaper than to replace it (Camilleri et al. 2005, Soul and Hamdy 2012).

*"Severe distortions have emerged as a major obstacle to the cost-effective fabrication of such lightweight structures"*

(Huang et al. 2003)

The industrial control of weld distortions is achieved by the use of empirical formulas, based on past results, to prevent distortion or rectifying work. However, for large complex structures, empirical formulas can rarely be applied (Bachorski et al. 1999). The alternative is to use numerical modes based on finite element analysis. The use of numerical simulation may have high hardware requirements and is time consuming (Deng and Murakawa 2008). In spite of this, Deng and Murakawa 2008 further state that correcting the weld distortions is more expensive than preventing it. The use of FEM simulation allowed not only to successfully predict weld distortion, as well as acquiring a better understanding of the weld distortion phenomena. Based on this knowledge, proper mitigation methods to prevent weld distortion were developed (Seyyedian Choobi et al. 2012). Some of the techniques applied to correct the weld distortions are the Flame

Straightening, the Cold Bending, the Press Straightening and the Laser Shock Processing (Feng 2005 and Gannon et al. 2010). Other thermal techniques can be used to correct distortion such as: Spot Heating, Line Heating and Wedge Shaped Heating (Lucas et al.). Feng 2005 states that the flame straightening method is very time consuming as well as very costly and requires qualified labour to perform. Feng 2005 further states that the straightening machines are expensive components, especially for large structures.

# 6. CONCLUSIONS

In this thesis, an analysis of the existing types of weld distortions and the weld distortions mechanisms is performed, based on an extensive literature survey.

The following aspects were covered:

- The distortion mechanisms and their relation to the heat sources used in welding.
- The methods used to quantify weldings distortion.
- The developed manufacturing methodologies to avoid weld distortion.
- The weld distortion impact in the economy of welded construction industries.

From the literature review, it was concluded that:

- There is a clear relation between the analysed geometrical parameters such as the plate width and the plate length, and weld distortion.
- The "V" and "X" shaped weld grooves effect on weld distortion are well established, however there is a lack of information regarding the other weld groove shapes and joint types.
- There is a clear relation between the phase transition of both base and weld metal and the weld distortion.
- There is a clear relationship between the variable welding parameters, such as the current intensity, the electric voltage and the weldings speed, and weld distortion.
- The effect of the use of constraints on weld distortion is well defined.
- There is no consensus in the published literature regarding the plate thickness effect on weld distortion.
- Although there is extensive literature regarding the base metal properties effect in FEM simulations, there is few articles regarding its direct effect on weld distortion.
- There is few literature regarding the heat source effect on weld distortion, namely, the welding methods used.

Several methodologies used to prevent weld distortion and methods used to quantify the weld distortion are described. The efficiency and applicability of these methods and methodologies is discussed. A table containing various distortion-control techniques, their benefits and detriments is presented.

Various methods used to quantify the weld distortion were presented and described. It was mentioned the type of distortion that each method can efficiently measure.

A study on the economic impact of weld distortion is performed, although there is little literature available on the matter. Few articles quantify the economic impact of weld distortion and little information is given regarding weld distortion correction.

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# APPENDIX A

## Appendix: Distortion control techniques

**Table A1 Minimize welding heat input**

| Technique | Benefits | Detriments |
|---|---|---|
| Improve fit-up | • Reduction in weld size<br>• Reduces all forms of distortion | • May require more time to fit<br>• Upstream operations must be controlled<br>• Investment in fitting aids |
| Minimize tack weld size | • Reduction in weld size | • Requires more fitter training<br>• Additional QC needed<br>• May require different welding process for fitting |
| Optimize process parameters | • Increase welding speed and reduce heat input | • Less applicable to manual welding |
| QC program to reduce overwelding | • Reduce all forms of distortion | • Requires additional training and vigilance<br>• Requires better fitting |
| Increase use of mechanization | • Increase welding speed and reduce heat input<br>• Improve weld consistency | • Less flexible<br>• Joint access limits applicability<br>• May increase setup time |
| Deploy low-heat input welding processes | • Increase productivity and reduce heat input | • Capital investment<br>• New procedures<br>• May require better fit-up |
| Reduce weld repairs | • Improve productivity<br>• Reduce heat input from extra welding | • Requires additional training and vigilance<br>• May need to reduce cosmetic appearance requirements |

**Table A2 Maximize restraint**

| Technique | Benefits | Detriments |
|---|---|---|
| Optimize fit-weld sequence | • Reduces dimensional variability | • Requires tighter control of operations |
| Use back-step sequence | • Reduces rotational distortion | • Less productive<br>• Not easily automated |
| Employ tooling/ fixtures | • Reduces angular and buckling distortion | • Tooling investment<br>• Additional operations to restrain and release components |
| Remove tabbed cutouts after welding | • Increases buckling resistance | • Subsequent operation required to remove cutouts |
| Employ egg-crate construction | • Increases resistance to all forms of distortion | • More difficult to fit<br>• Makes welding automation difficult |

**Table A3 Design modifications**

| Technique | Benefits | Detriments |
|---|---|---|
| Reduce stiffener spacing | • Reduces buckling tendency | • May increase weight if stiffener size not reduced<br>• More welding required |
| Increase plate thickness | • Reduces buckling tendency | • Increases weight<br>• May increase angular distortion<br>• Higher heat input for butt welds |
| Reduced cutouts | • Reduce buckling tendency | • Increases weight |
| Reduce insert thick-thin transitions | • Reduce distortion in thin plate | • Increases weight |
| Reduce design weld size | • Reduce all forms of distortion | • Less factor of safety |
| Employ intermittent welding | • Reduce buckling distortion | • More difficult to control segment length and location<br>• May be corrosion, fatigue, and shock issues |
| Beveled T stiffener joint | • Reduce angular distortion | • Adds a manufacturing operation |

**Table A4 Active mitigation approaches**

| Technique | Benefits | Detriments |
|---|---|---|
| Balance heat input | • Reduces angular distortion<br>• In use for double-sided submerged arc welding | • Requires double-sided welding<br>• No benefit for buckling |
| Presetting butt joints | • Can eliminate angular distortion | • No benefit for buckling<br>• Degree of preset depends on plate thickness and welding procedure<br>• Special tooling required |
| Precambering beams | • Can counteract bowing and buckling distortion | • Difficult to fit and weld beams<br>• Special tooling required |
| Back-bending fillet joints | • Can counteract angular distortion | • Major tooling investment<br>• Applicable only to angular distortion on longitudinal stiffeners<br>• Degree of preset depends on plate thickness and welding procedure |
| Forced cooling | • Can reduce buckling distortion | • May adversely affect steel weld properties |
| Thermal tensioning | • Reduces buckling distortion<br>• Shown effective in shipyard tests | • Procedure dependent on panel design<br>• Not tested for complex panel geometries |

SOURCE: (Conrardy et al. 2006)