UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

CONTROL OF RESIDUAL STRESSES AND DISTORTION IN WELDED STRUCTURES FOR ENERGY APPLICATIONS

by

CHRISTOS SOUKIAS

MSc. Diploma in Mechanical Engineering, University of Thessaly, 2021

SUPERVISOR TEACHER

Dr. GR. N. HAIDEMENOPOULOS

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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Thanks

I would like to thank all those who supported me during the postgraduate program, my family and all my friends who supported me in this endeavor. I would also like to thank all the teachers of the program who with patience, method, passed on their knowledge and experience. I would especially like to thank Dr. Gr. Haidemenopoulos who guided me to complete this effort of mine with my diploma thesis.

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Abstract

The present thesis, which was prepared under the supervision of Professor Dr. Gr. N. Haidemenopoulos of the School of Mechanical Engineering of the University of Thessaly, aims to study the residual stresses and distortions that occur in welding of steel structures as well as the ways in which we control the residual stresses and distortions caused by of welds.

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Chapter 1

Residual stresses

General

Residual stresses can be characterized as the stresses that exist in a material or solid body which is still and is in balance with its environment. These stresses balance each other within an area of the body or material, appear without external charges and are not necessary to maintain the balance between the body in which they occur and its environment. When forces are applied to a material, this results in stresses and strains. Stress is the internal reaction force of the object (per unit area). For a uniform distribution of internal reaction forces, the stress can be calculated as the force (F) applied to the material per unit area (A) exercised:

$$\sigma \text{ (stress)} = \frac{F}{A} \text{ (N/mm}^2\text{)}$$

The specific distortion is interpreted as the size of the distortion per unit length of the object when a charge is applied to it. The specific distortion is calculated by dividing the total distortion of the original size by the original size:

$$\text{ειδική παραμόρφωση} = \frac{\Delta L}{L_0} = \frac{\sigma}{E}$$

where:

ΔL: the longitudinal distortion of the object,

L_O: the original length of the object;

σ: deformation stress,

E: the modulus, or modulus of Young, of the material of the object.

The residual stresses can have both positive and negative effects on the component - material in which they appear. On the one hand, they can be detrimental when they reduce the strength of a material to an externally imposed load by reducing the life span of a component. On the other hand, they can be used for the design of materials and components of improved properties and greater durability. In modern mechanical design there is increasing interest in how residual stresses affect mechanical properties. This is because a failure, which in many cases is unexpected, can be caused by the combined action of residual stresses (internal) and externally imposed. In practice it is highly unlikely that any mechanical component will be fully free from residual stresses introduced during the manufacturing process. In fact, the residual stresses are much more difficult to predict than the stresses introduced by operation, with which as we have already mentioned they interact. The great importance of residual stresses in mechanical engineering applications is therefore easily perceived. For this reason, it is very important that we have reliable methods of measuring the residual stresses and, in addition, that for each method we can understand the level and quality of the information it provides us.

Classification of residual stresses

The residual stresses according to the cause of the stresses are divided into the following categories:

- Thermal residual stresses which cause only elastic deformations.
- Permanent residual stresses generated by the effect of plastic deformations on a body identified as elastoplastic.
- Permanent remaining stresses, which are created during the uneven heating and cooling of the body.
- Permanent residual stresses arising from phase and structural transformation

The second category relates to the classification of the residual stresses according to the size of the body mass volume, in which they are balanced. The length attribute, which is the length at which the same stresses are balanced, can be used for this classification. The following categories can be distinguished:

- Residual stresses type-I, which balance in macroscopic dimensions (characteristic length equal to the scale of construction). The same stresses of this category can be calculated using continuous models, which do not take into account the polycrystalline or polyphasic nature of the material and usually of finite elements.

- Residual stresses type-II, which balance into small (microscopic dimensions) of the volume, i.e. the boundaries of the adjacent grains of the material (typical length about three to ten times the size of a grain). The source of these stresses is grain orientation.
- Residual stresses type-III, which balance within the crystal lattices (characteristic length less than grain size-individual dimensions).

The third category relates to the classification of the residual stresses according to their position in the space are the following:

- Single-axial residual stresses, when developed in one direction (negligible in the remaining two).
- Biaxial residual stresses when they are developed in two directions (negligible in the third).
- Triaxial residual stresses when developed in all three directions.

A very important property of the residual stresses is the fact that they interact with all the construction (especially the welding stresses), which creates favorable conditions for not expanding any fractures formed.

In general the residual stresses can increase or decrease the average stress value by one charging cycle. As a tensile load increases the mean applied stress it is necessary (with appropriate application of a counter- residual stresses) to reduce the range of the total stress so as to leave the life of the material unaffected.

Stresses in welds

The residual stresses in metal structures develop during various processes such as:

- formatting processing
- Hardware removal machining
- layout processing
- thermal and surface treatments

- assembly operations

In melting welds, local heating of the material causes the development of thermal stresses and deformations during welding. Stresses and deformations remain after welding can have a significant effect on the mechanical strength of welds. The high tensile stress remaining in the seam area can cause cracking or premature failure of the construction. The compressive remaining stresses in the base metal can reduce the strength of a sheet to buckle. At the same time the deformations of the welds can get high values, above the limits of acceptable tolerances and the construction is unsuitable for use.

In the case of welds, the residual stresses are classified into two classes according to the mechanism which causes them:

- Stresses caused by forced trapping of components
- Stresses caused by non-uniform distribution of plastic and thermal deformations

In relation to all areas where the residual stresses are found, what we will be particularly concerned about is the effects of the current stresses on welding applications. Local heating and subsequent cooling of the metal takes place during welding. As welding is cooled, the contraction occurring in the melting zone is prevented by the relative rigidity of the remaining base metal. The obstruction of the free variation of the dimensions of the heated zone (contraction of the welding zone) appears as elastic deformation (at the level of the yield stress) which ultimately leads to the emergence of the residual stressing. The emerging stresses in the welding area are balanced by anti-formity stresses in the base metal area. The restriction of freedom of deformities leads to the emergence of stresses, which are in the following formula:

$$\sigma = E.\alpha_t \, \Delta t \qquad (1.1)$$

where:

E: Young`s modulus of the material,

a_t: linear coefficient of thermal expansion, Δt:temperature difference of the heated and non-heated metal zones..

The E and a_t values vary greatly in the area of the temperature displayed during the welding process. These changes are given by bills based on temperature. The plastics limit of the metal is also substantially altered.

The great difference in welding temperatures is also the cause of the formation of the plastic deformations leading to the appearance of the residual stresses. These plastic deformations, in terms of the low mechanical properties at high temperatures and the low volume of the heated metal (zone of weldment) relative to the total volume of the welded component, show their maximum values in the area of the connection.

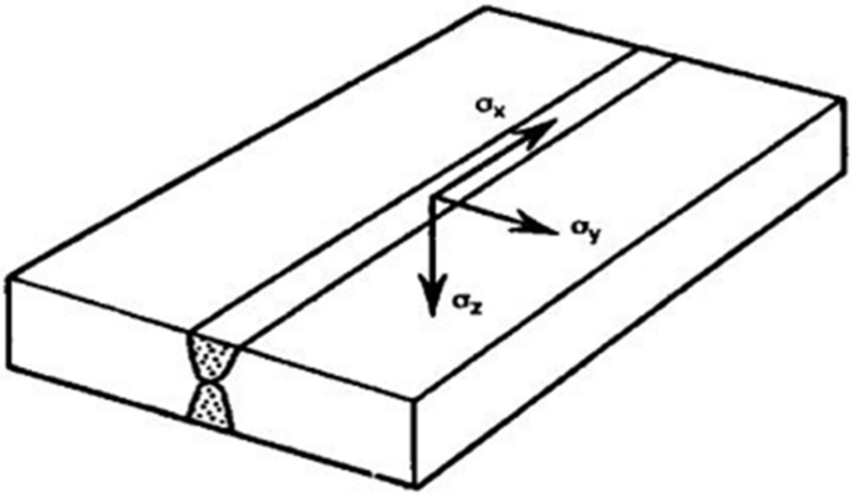


Figure 1: Stresses in welding

Figure 1 shows the stresses usually used in a plate-level edge weld (front) to describe the direction of stresses in terms of the seam direction (Conventional direction positive): σ_x longitudinal stress (parallel to the seam), σ_y transverse stress (perpendicular to the seam) and σ_z stress across the thickness of the plate.

Figure 2a shows a simple construction consisting of two fixed supports Σ_1 and Σ_2. Two bars P_1 and P_2 are connected to the supports. The middle P_M bar has a shorter length than the two side bars and is only connected to the Σ_1 bracket. If the P_M rod is drawn and forced to be attached to the Σ_2 bracket, then the system will be loaded. That is to say, it will obtain residual stresses. The P_1 and P_2 rods shall be loaded to grief while the P_M bar is loaded to tensile. The σ_m stress of the middle bar shall be twice the σ_1 stress of the side rods, i.e.:

$$\sigma_m = 2 \cdot \sigma_1 \qquad (2)$$

so that $\int \sigma dA = 0$ (3)

The residual stresses σ_m and σ_1 that are developed in Figure 1α are due to the forced attachment of the P_M rod to the Σ_2 bracket. Figure 1b shows the distribution of the residual stresses at intersection AA'.

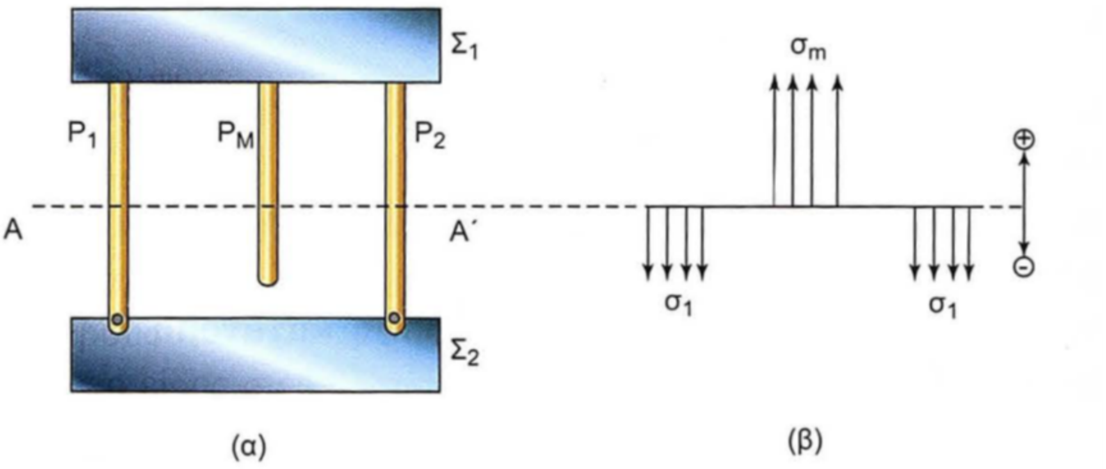


Figure 2:The three-bar configuration. The forced trapping of the middle bar (a) causes the development of residual stresses (b).

Residual stresses from non-uniform distribution of plastic deformations

Here we will analyze how uneven heating and cooling of a body can cause the development of non-uniform plastic deformations, which causes the development of residual stresses. In Figure 3a all three bars have the same length. While no external loads are imposed. Then heat only the middle bar until the temperature T_Γ and then cool it to the ambient temperature T_0. During the thermal cycle, the P_1 and P_2 rods remain at ambient temperature T_0. Figure 3b shows the stress change in the P_M middle bar over the heat cycle. When heating the middle bar develops a compressive stress, because the bars P_1 and P_2 prevent the expansion of the middle bar.

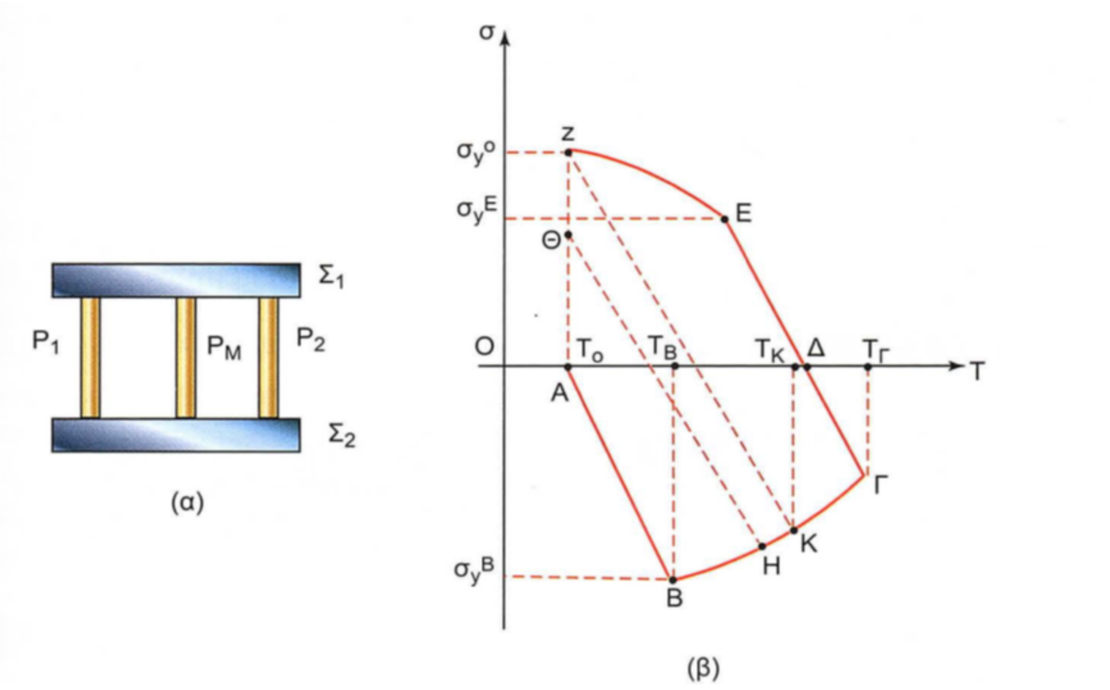


Figure 3:Three bar arrangement by heating only the middle bar (b) Change in stress on the middle bar as a function of temperature

As the temperature increases the stress follows line AB and remains elastic until the stress reaches the value σ_y^B and the yield stress of the material at temperature T_B . From this point the stress follows the change of the metal yield stress with the temperature, that is the curve BΓ. At point Γ (temperature $T_Γ$) the cooling of the middle bar begins. The bar starts to discharge by discharging, it is always elastic, so the stress on the middle bar follows the ΓΔ line. When the bar is fully discharged (σ=0 at point Δ) it remains warm. Its continuous cooling causes contraction but is blocked by the rods P_1 and P_2 without deforming them and the tensile stress on the middle rod develops. As the temperature decreases this tensile stress increases according to the ΔE line. At point E and at T_E temperature the stress reaches the yield stress σ_y^B of the material. With the continued cooling of the rod the stress is changed according to the EZ curve, the yield stress of the material is changed by lowering the temperature. At room temperature T_0 (point G), the σ_Z stress of the rod is equal to the material yield stress. The σ_Z stress of the middle rod is tensile while on the bars P_1 and P_2 compressive stresss equal to $\sigma_Z/2$.

The residual stress will be zero if all three rods are subjected to the same thermal cycle at the same time. However, since only the medium is subjected to the heat cycle, we are led to the development of a residual stress. In the case of the middle bar, the development of the residual rod is due to the non-uniform distribution of the thermal-plastic deformation of the rod system in the transverse direction y. In Figure 3 at any temperature above the T_K temperature the heating of the rod would cause a residual stress as much as the yield stress at room temperature σ_y^0.

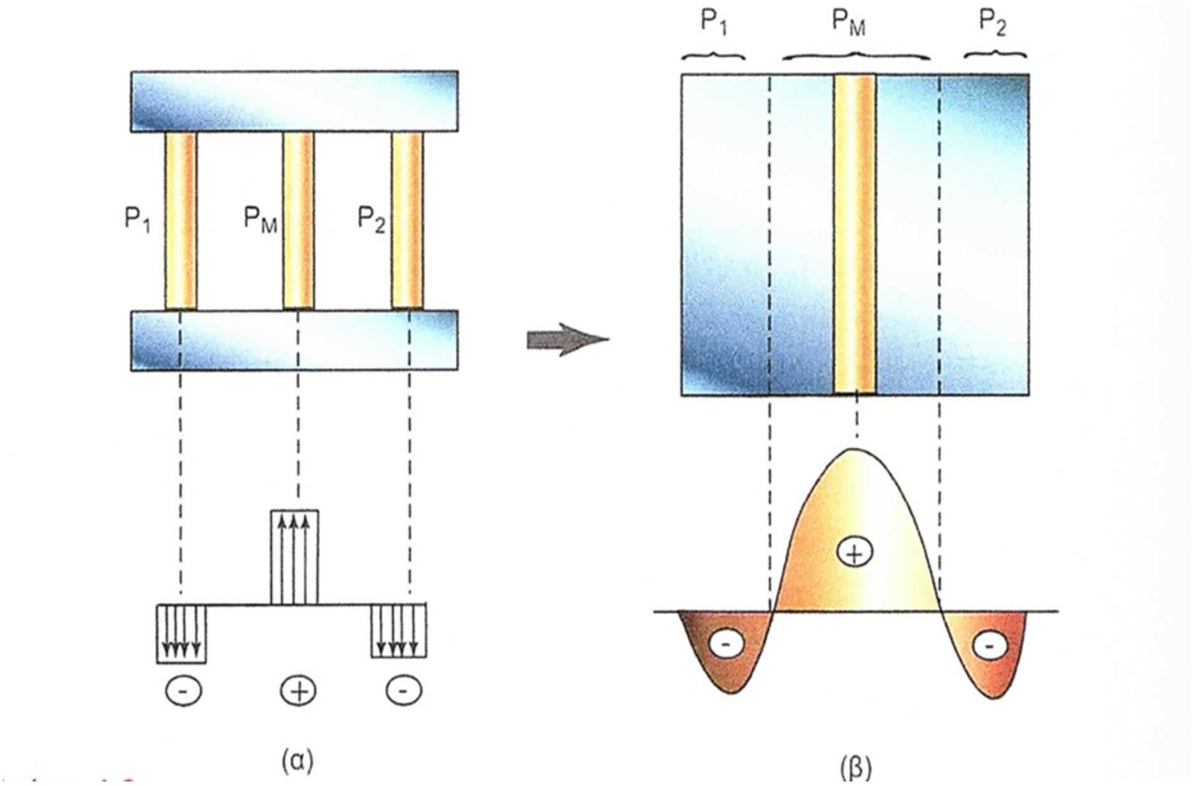


Figure 4:Matching the development of residual stresses in the layout of the three bars with the development of residual stresses in welds

Distributions of residual stresses

The residual stress developed in welded pieces are transverse ςy and longitudinal. Σ_x which longitudinal are tensile in the seam area and decrease in the distance y from the weld axis to become compressive. The distribution of the longitudinal stress $\sigma_x(y)$ is expressed as:

$$\sigma_x(y) = \sigma_{\max}\left[1-\left(\frac{y}{b}\right)^2\right]e^{-\frac{1}{2}\left(\frac{y}{b}\right)^2} \qquad (4)$$

where $\sigma_{\max}$ is expressed as the maximum tensile strength and b is the tensile band width, which is several times the width of the welding metal. The transverse contraction of the metal is mainly responsible in the seam area for inducing transverse stress in σ_y. If external constraints are imposed on a plate weld by external constraints then the distribution of the residual stresses changes.

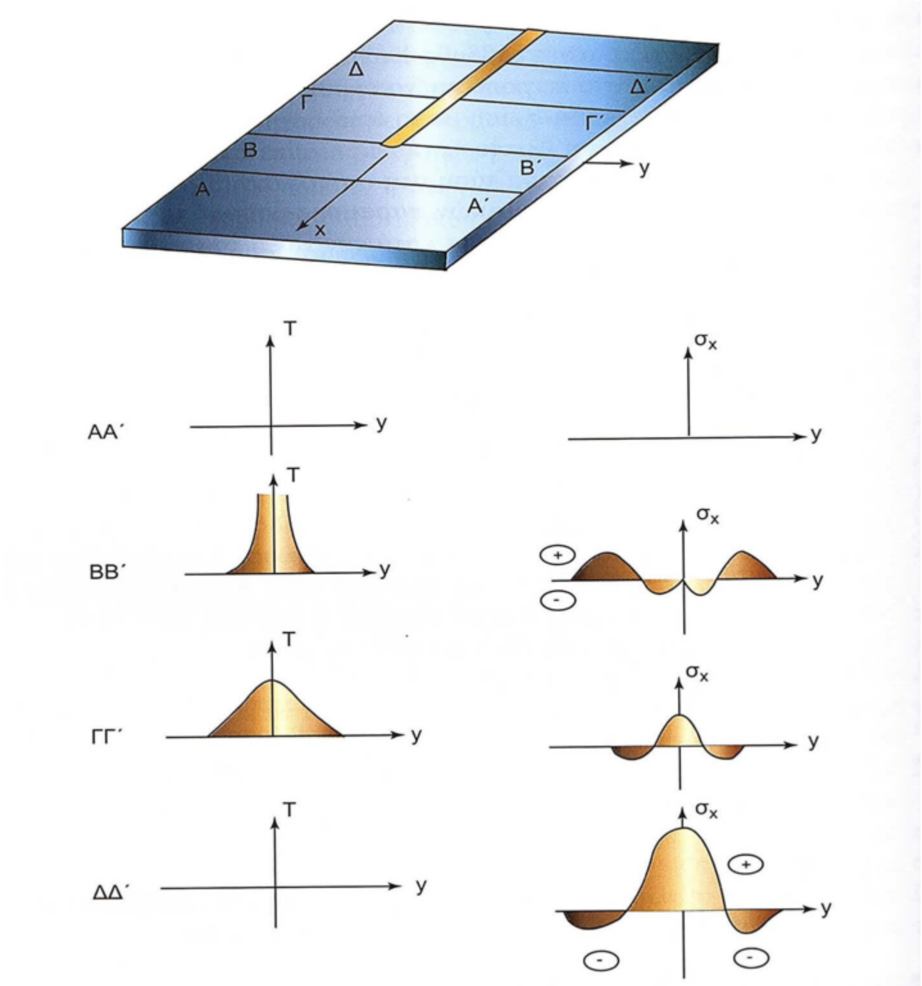


Figure 5: Correspondence of temperature distributions and residual stress development in welds.

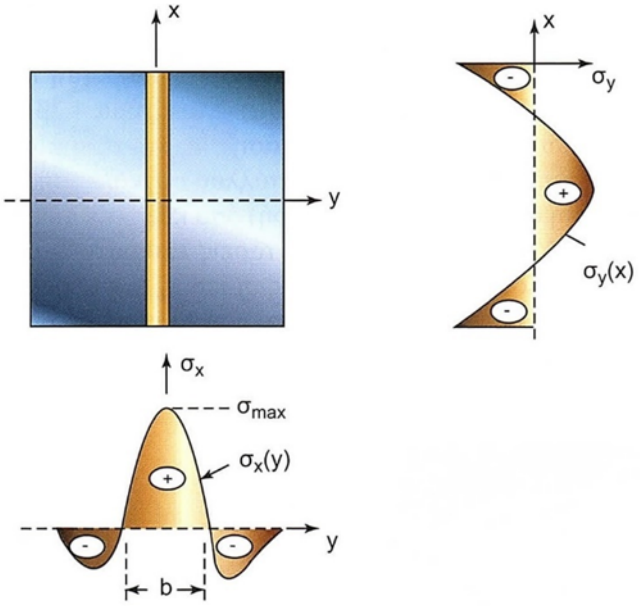


Figure 6: Distribution in welding of residual stress in transverse and longitudinal direction

The distribution of longitudinal residual stresses in σ_x is shown in Figure 6. It should be noted that tensile contraction occurs on a surface about ten times the surface of the weld. This is due to the fact that the area around the seam is subject to local plastic deformation after the removal of the heat source. We observe that tensile tensions of large size develop in the area around the weld, they gradually decrease, to become compressive at a distance from the welding line equal to sometimes the width of the welding metal (compensation of tensions in the base metal area).

Circular disk welding is a welding that is usually used in hole plate repairs. In Figure 7 the radial stress σ_r and the girth stress σ_θ are caused by the contraction of the welding metal at the periphery parallel to the seam as well as perpendicular to the seam in the direction of the radius. Both stresses σ_θ and σ_r are tensile as the outer plate prevents the contraction of the circular disk while due to the stress balance the σ_θ is converted into compressive outside the circular disk.

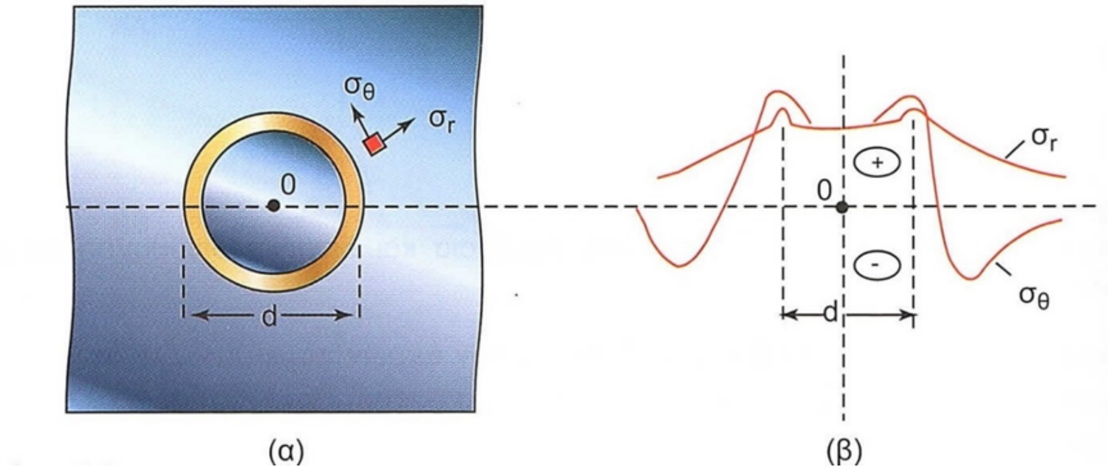


Figure 7: (a) Welding of a circural disk on a plate, (b) distribution of residual stresses σ_θ and σ_r

In the girth weld figure 8 in a pipeline both the longitudinal σ_Z and the girth σ_θ, near the weld are tensile while away from the weld are transformed into compressive.

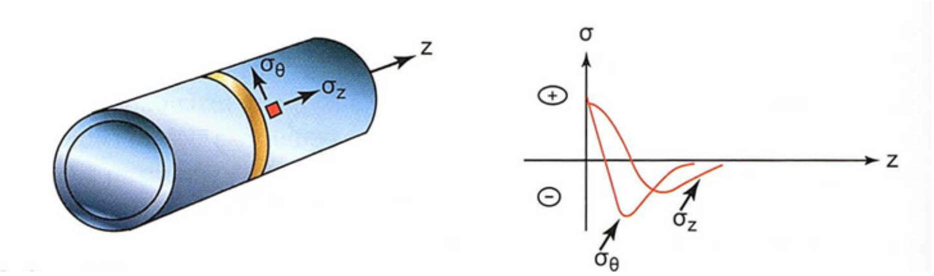


Figure 8: Peripheral welding to a pipeline and distribution of residual stresses

Factors affecting the residual stresses

Effect of welding length

To fully develop the residual stress, the weld must have sufficient length. The length effect is shown in Figure 9 for frontal welds. The residual stress is set to zero at the ends of the plate and maximized at the midpoint of the length. The residual stress increases the length from L_1 to L_4. It seems that for a length over L_4 the size of the residual stress remains constant. In the general case it appears that sufficient welding length L_0 is required for the full development of the residual stress. L_0 depends on the geometry and welding method.

Effect of the plate width

The width of the plate after experimental observations shows that it has no influence on the size of the residual stress since the width is much larger than the range of the residual stress field.

Effect of welding series

The welding order does not have a significant effect on the size and distribution of the residual stress, but only has a significant effect on the deformations of the welds, and this has been observed by experimental measurements.

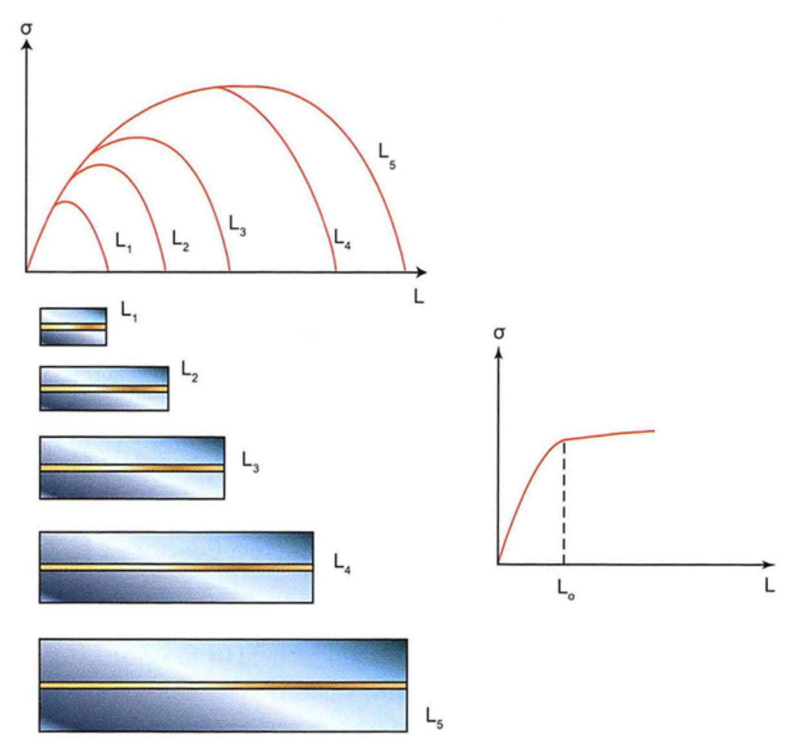


Figure 9: Effect of welding length on residual stress

Effects of residual stresses on mechanical behavior

Welded mechanical structures shall be subjected to external mechanical loads, static or dynamic. In general, external stresses and remaining stresses are added vector. This means that the applied tensile stresses increase with the addition of tensile residual stresses but decrease by the compressive residual stresses. Also in the case where compressive stresses are applied in a construction, they are reduced by the tensile stresses remaining but increased by the compressive stresses remaining. This means that the tensile fracture or the buckling of a structure can occur at significantly lower external loads than those, which were taken into account when designing the structure.

The effect of residual stresses on the mechanical behavior of welded structures depends on the size of the extrernal loads. The interaction of an externally applied mechanical stress with the residual stress field of a weld shall be studied. Figure 10 shows the simple case of frontal welding on a laminate, which undergoes a uniform tensile stress σ. The O curve corresponds to the distribution of the longitudinal residual stress immediately after welding. As mentioned, close to welding prevail high tensile stresses, while away from welding the stresses are compressing. Curve 1 corresponds to the distribution of stresses after application of uniform tensile stress $\sigma=\sigma_1$. The stresse σ1 is added to the residual stress and thus tensile stresses close to the metal yield stress are prevailing close to the weld, and stresses have also become tensile away from the weld. Curve 2 corresponds to the application of a higher tensile stress $\sigma=\sigma_2$, which results in a more uniform distribution of stresses relative to curve 1. Thus it is observed that with the increase of external stress, the effect of the residual stress of the weld on the distribution of stresses decreases. Curve 3 corresponds to the application of an even higher stress $\sigma=\sigma_3$, which causes plastic deformation of the whole cross section of the plate. Beyond this point the effect of the residual stress of the weld is zeroed. Curves 1, 2 and 3 correspond to the distributions of the residual stress after discharge of the plate from the stresses σ_1, σ_2 and σ_3 respectively. It can be observed that the distribution of the residual stress is homogenized with respect to the initial distribution (curve O). Indeed the homogenization and the corresponding reduction of the residual stress is more pronounced the higher the externally applied stress σ. On the basis of the above, the following conclusions are reached:

- With the increase of external loads, the effect of the residual stress of the weld on the distribution of stresses on the plate decreases
- The effect of the residual stress is almost nil when the external loads cause generalized plastic deformation

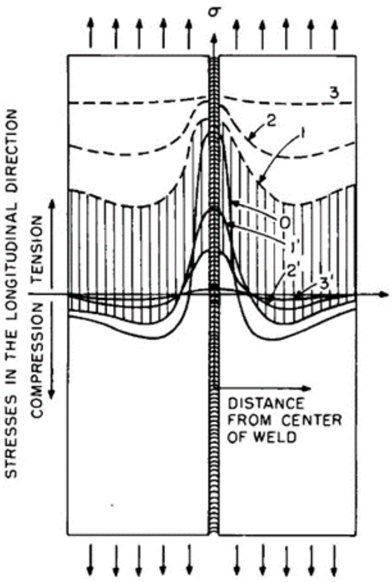
- Residual stresses decrease when construction undergoes repeated loading
- Remaining stresses decrease when construction undergoes high mechanical loads
- The effect of the remaining stresses is as great as the smaller the external mechanical loads

During the hydraulic test on which welded pressure vessels are subjected, the vessel plates (and thus the welds) are charged at a stress greater than the working stress. The main purpose of this test is to detect errors and yields, but it serves a further purpose, reducing the residual stresses in its welds of the vessel. Also the residual stresses affect phenomena that occur mainly if low external loads are applied to a construction. These phenomena concern brittle fracture, fatigue and corrosion.

The brittle fracture of welded structures can occur at significantly lower loads due to the presence of a high tensile residual tension in the weld. Similarly, the fatigue life of a welded construction can be affected, where the presence of tensile residual stress combined with possible welding errors (pores or microcracks) in the weld area leads to rapid formation of fatigue crack. Also, the resistance of a structure to ergocorrosion is reduced due to the presence of a high tensile residual tension in welding.

However, compressive stress can also have a negative impact on the mechanical behavior of a construction. These stresses can cause buckling either by themselves or in combination with compressive exterior loading of construction. This issue is particularly important in light structures, where thin sheets are used. Also, the local buckling of some critical building block can lead to a collapse of the structure due to load-carrying on other building blocks, which cannot withstand additional loading.

All of the above leads to the conclusion that measures should be taken in welded structures to reduce residual stresses, especially in those cases where the effect of residual stresses is expected to be significant.



Curve 0: Residual stresses in the as welded condition.

Curve 1: Stress distribution at σ=σ1 •

Curve 2: Stress distribution at σ=σ2.

Curve 3: Stress distribution at σ=σ3 •

Curve 1' Distribution of residual stresses after σ=σ1 applied and then released

Curve 2' Distribution of residual stresses after σ=σ2 applied and then released.

Curve 3' Distribution of residual stresses after σ=σ3 applied and then released.

Figure 10: Distribution of stresses in butt welded by application of uniform tensile stress by presence of residual stress

Main factors relating to the existence of residual stresses

The issue of residual stresses that occur in welded structures is generally considered under the concepts of range, direction, spatial arrangement, and the diversity of these stresses. The main factors determining what kinds of residual stresses and whether these will occur in a welded construction are the following:

The existence of stresses due to the procedures followed for the manufacture of the parts to be welded. These stresses will play an important role in the areas away from the seam, where the "overall" residual stresses after the weld will arise as superposition of the stresses introduced into the material due to the weld and the stresses that exist in the piece due to its manufacturing processes. The superposition effect can give stresses in either the rubber, elastoplasticity, or the purely plastic area depending on the range of the cumulative stresses and the mechanical properties of the material.

The residual stresses that predate welding can be due to thermal or mechanical processes during the construction of the various pieces. Some typical processes that can lead to the birth of sustained stresses of this category are casting, extrusion, various heat treatments, dyeing and carbonization. The processes likely to give rise to pre-existing stresses are also included in the category of processes that may give rise to pre-existing stresses. Some of these are warming-up, containment, bending and alignment. In many cases to avoid the introduction of residual stresses during the application of some of the above processes, they are followed either during or after stress mitigation techniques which can reduce these range by up to half the material leak limit. One such process is the reheating of the material followed by a slow cooling rate.

In general, the likelihood of pre-existence of remaining stresses due to manufacturing processes should always be taken into account when estimating the residual stresses in welded structures. In experimental procedures where the objective is to measure the residual stresses in welded pieces, it is recommended to measure the residual stresses in areas not affected by welding, or in pieces before being welded, so that there is a good estimate of the range of pre-existing residual stresses.

The properties of adhesion material and base material, including composition, microstructure, thermal and mechanical properties. The simplest hypothesis related to the maximum tensile residual stress range in a weld is how this equals the yield stress of the base material or adhesion material. It is a reasonable assumption that applies to most but not all materials. In general tensile residual stresses will be approximately equal to the material yield stress if the following two conditions apply:

(a) if there is a restriction of the free contraction of the heated material (it is a matter related to the geometry of the adhesion)

(b) if the deformation of thermal contraction from the high temperature in the environment is greater than the deformation corresponding to the yield stress of the material. This is the case when the relationship:

$$a \cdot \left(T_s - T_0\right) \geq \frac{\sigma_y}{E} \qquad (5)$$

where:

α is the coefficient of thermal expansion,

T_s the high temperature which here is defined as the temperature at which the yield stress falls to 10% of its value at ambient temperature,

T_o the ambient temperature,

E Young modulus and

σ_y the material yield stress at ambient temperature.

The classic case where the second condition is met and thus remaining stresses of the yield stress arise, are all austenitic steels.

The problem of sustained stresses is compounded by the property of phase transformation, which is notable in many materials. Phase transformation introduces additional deformations thus and stresses contributing to the volume changes taking place in the material particularly when taking place at low temperatures during cooling after welding. The problem of the same stresses from phase transformation is not essential when bonding soft carbon steels because transformations take place in the temperature range, in which the elasticity limit is low and changes in volume are easily balanced by plastic deformations. Conversely, in the case of alloy steels, the phase transformations are done at a lower temperature, and so here the effect of the phenomenon on the state of the residual stresses is great.

The actual welding process chosen including the preparation of the welded elements (which can introduce residual stresses pre-existing of the weld or even reduce them), the conditions under which the weld is performed and the order in which the passes are laid on seams requiring the deposition of more than one pass.

A typical example is the process of warming-up that is followed several times in the preparation of the welded elements. Experiments conducted on low-thickness laminate level welding samples showed that preheating of the pieces can help eliminate residual stresses.

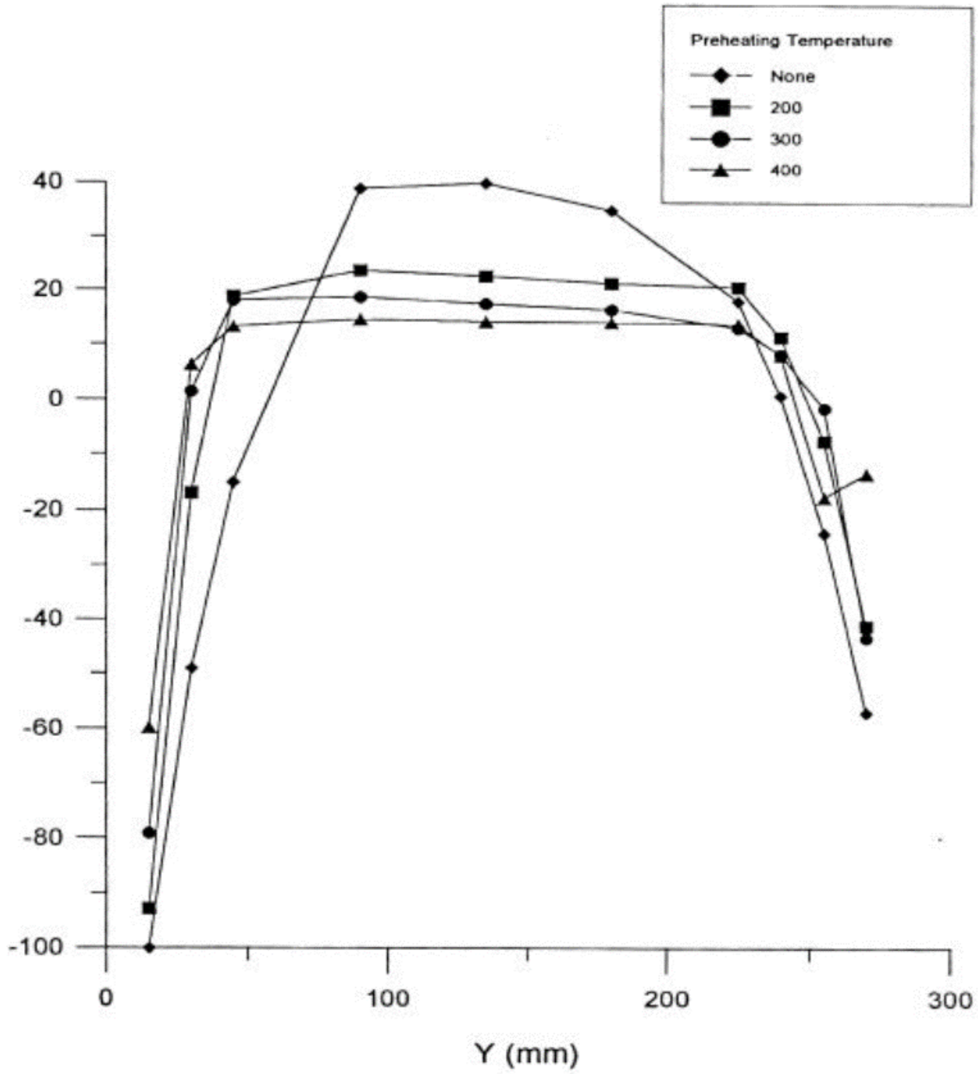


Figure 11: Pre-heating of the welded pieces at 200, 300 and 400 °C. The reduction of residual stresses is visible. (visualization of the transverse residual stresses)

Another important parameter related to the conditions under which welding is performed and can differentiate the effect with respect to the residual stresses is the movement speed of the electrode. Experiments that have been done by differentiating the speed with the remaining parameters of the adhesion, have shown that a high speed not only reduces the volume of the base material affected by the heat being pumped from the source but also slightly reduces the residual stresses as shown in the next figure

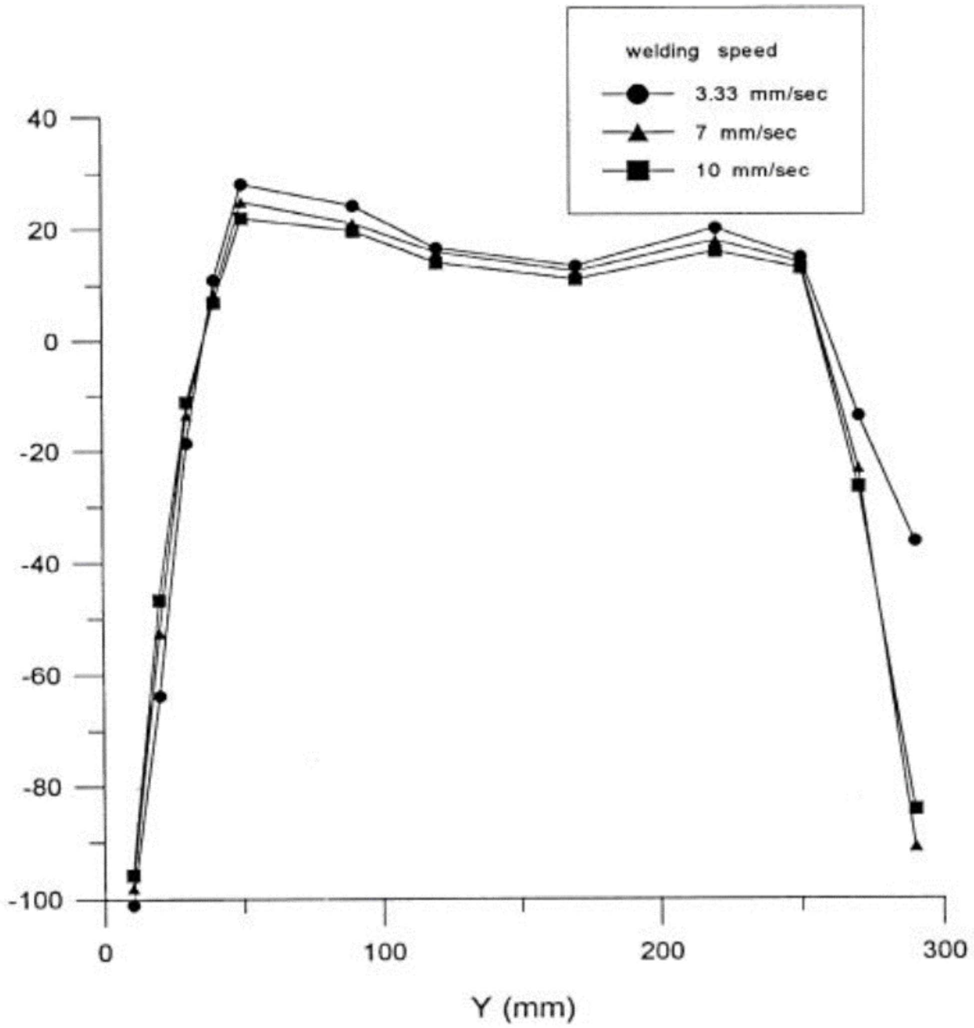


Figure 12: The effect of electrode velocity on transverse residual stresses

Using welding methods with increased electrode velocity creates thinner isothermal curves in the material. The smaller range of these curves influences the transverse shrinkage in the plate-plane weld, not conducive to it, thus explaining why higher electrode speeds generally lead to lower residual stresses.

The geometry (dimensions) of the welded elements and in addition the constraints imposed on the pieces such as the use of vise, orientation or temporary seams (e.g. bets) in order to facilitate the operator in the implementation of welding. The constraints on a welded connection can generally be described as the resistances projected on the pieces against their free expansion due to the heat being pumped into them. The concept of constraint seems fairly simple but in fact exhibits some complexity as it differentiates in direction and position in a weld and can vary even when the same piece is glued. The constraints imposed on the welded parts are influenced by a wide range of factors including the geometry of the welded elements (namely the cross-section of the structure which the greater the greater the stresses that will eventually arise), the auxiliary parts to be used (e.g. Pots, binders, etc.) and the order of placement of the solder required. Externally imposed restrictions contribute to the generation of residual stresses through welding stresses. This term is found in the literature to name the stresses arising from the reaction forces resulting from the attachment of the welded object, and to differentiate them from the same (or internal) stresses which contribute to the generation of the residual stresses arising from other causes (uneven heating and cooling, phase transformation) mentioned above.

Looking in more detail at the stresses generated by externally imposed restrictions with the help of experiments that have been done, we can first say that the residual stresses that arise in the three directions are completely different. This is because the imposed restrictions act differently in the three dimensions. The longitudinal contraction of the adhesion is significantly prevented by the elements welded, thus generating high tensile stresses during the thickness of the adhesion. The transverse shrinkage of each passage laid on the seam is prevented by previous passages, thus generating tensile stresses near the top surface of the adhesion, which interact with compressive stresses at the middle of the thickness and tensile at the bottom of the seam eventually creating a tensile average stress at the thickness of the laminate. The thickness remaining stresses are fully compressive; each passage is free to shrink in this direction when deposited so initially no stresses are created in the thickness. However, the compression of the central area in the transverse direction due to the shrinkage of the surface layers of the adhesion eventually gives rise to compressive stresses in the thickness direction.

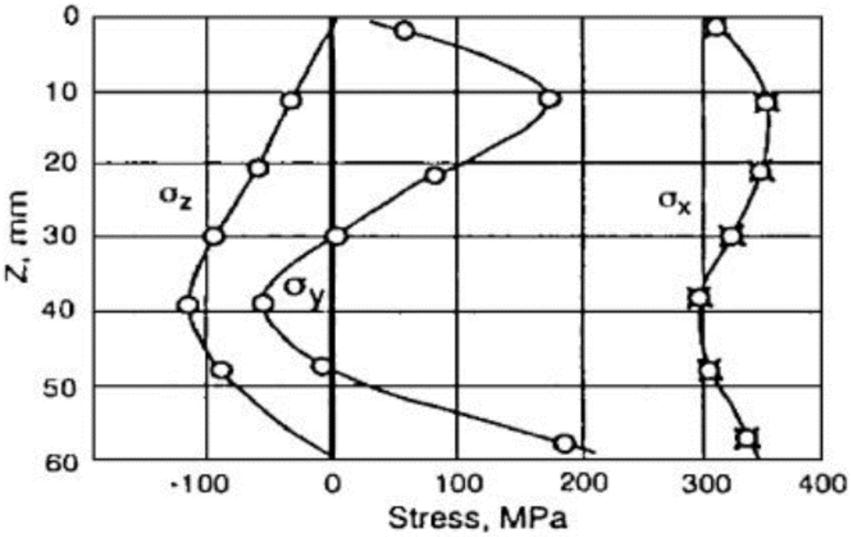


Figure 13:Residual stresses in the three directions created during welding of a significant level plate 60 mm. These stresses have been measured on the center line of the welding seam and their thickness distribution on the center line is shown. As it seems we have fully tensile stresses in the longitudinal direction, fully compressive in thickness and mixed in the transverse direction with the average stress however to be tensile.

The procedures followed at the end of welding or the thermal and mechanical loads received by the welded structure after its application at the workstation which may have led to the generation of new internal stresses or to the relief (smoothing) of existing ones (or parts thereof). This class of stresses (after the end of welding) will not concern us at all.

Methods for measuring residual stresses

General

The residual stresses are very difficult to predict with regard to operational stresses. That is why it is very important to have reliable methods to measure these stresses and to be able to understand the importance of the information they provide. The methods of measuring the residual stresses are initially divided into three major categories. These are: (A) The mechanical stress measurement methods. These methods are based on the control (supervision) of changes in the deformation of the controlled parts, either at the birth of the residual stresses, or after that by intentionally removing part of the material allowing the stresses to deflate. (B) Methods of measurement by refraction. These methods use the adjective of a radius of known wavelength in the material under consideration which through the refraction angle and interaction with any changes inside the material can “detect” elastic deformation. This deformation using an appropriate hardness value can be converted to a stress. (C) Other methods. These methods include magnetic and electrical techniques, ultrasonic methods, etc.

Mechanical methods for measuring residual stresses

Measurement by curvature

Curvature measurement is often used to determine stresses within coatings and layers (thin layers). Deposition of a layer can introduce stresses that cause curvature in the substrate, as shown in the next figure:

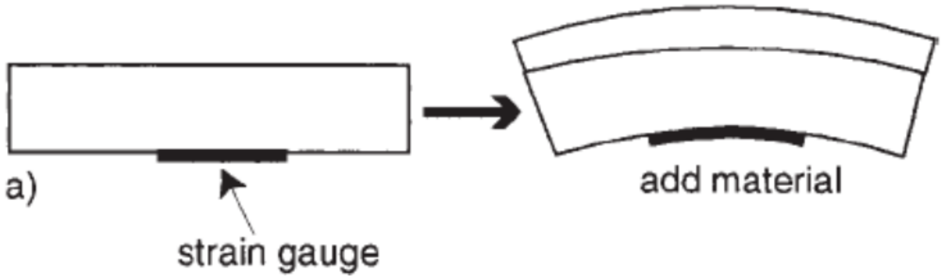


Figure 14: Measurement of residual stresses by curvature

The resulting curvature changes during layer deposition allow us to calculate the respective stress differentiations as a function of layer thickness. Curvature can be calculated either by contact methods (e.g. extended gravimeters) or without direct contact (e.g. video recording, laser scanning). Measurement is usually limited to thin strips to avoid multi-axial curvature and instability

Gunnert retention technique

The Gunnert has proposed a technique for measuring the residual stresses in weldments using the mechanical elonitometer of Figure 15. In this technique the Brinell balls, whose centers are separated by 9mm, Figure 15b, are placed in conical indents on the surface of the test piece. The shape of these indentations is shown in Figure 15c. Three indentation pairs are required to measure the residual stresses, but four pairs are usually used to improve the measurement accuracy. The indentation centers are located on the circumference of a radius of 4.5 mm. Measurements of the diametrically opposed distances are first taken. The difference between the two measurements gives an indication of the relief of the stresses. In a variant of the method, instead of the indents, four holes of 3 mm diameter are opened and their centers extend to the circumference of a circle of 9 mm diameter. These holes are 90° apart and extend to the entire thickness of the plate. Measurement of the antidiametrical distances of each pair of holes at various levels below the below the surface of the sheet before and after separation of the section bearing the holes. From these measurements, and using appropriate equations, it is possible to calculate the residual stresses within the sample. The application of the method requires surfaces to be horizontal, taking advantage of simplicity and easy repair of the specimen without having to be completely destroyed. In the event of misuse there is a high probability of incorrect measurement taking which is a disadvantage

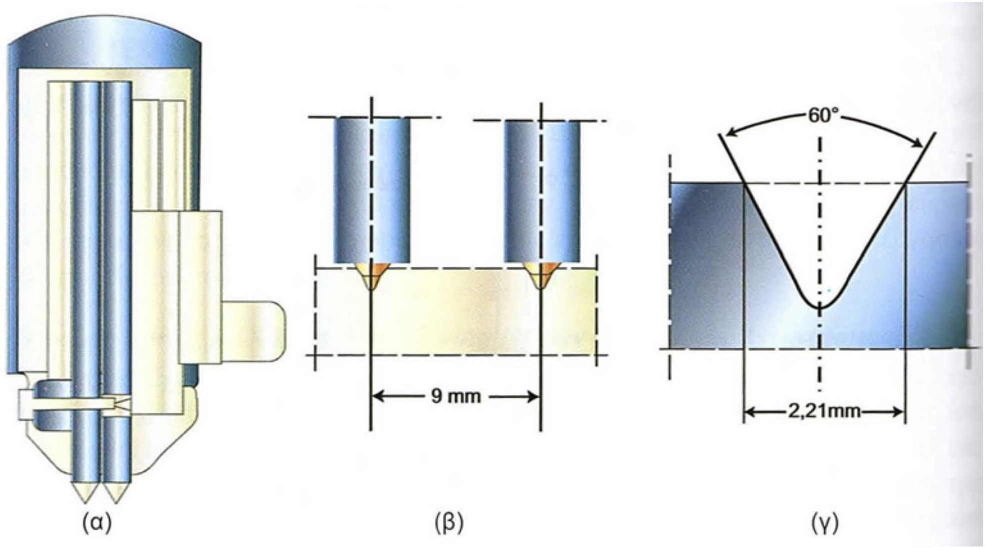


Figure 15: (a) Mechanical elongation meter, (b) Brinell balls and (c) Tapered recesses on test piece surface

Hole drilling measurement

This is the method that we will use in the experimental part and we will refer to it in more detail in the follow-up to this chapter. Quotes, we can say that with hole puncture in the area where previously (e.g. using an elonsimeter) deformation has been measured, the stresses are "relieved" providing us data for the "backward" calculation of the residual stresses.

Compliance method measurement

The fracture toughness method involves opening a small cutaway to monitor the expansion of the stresses in the vicinity of the cutaway using an elonsimeter string. By adjusting (spin) the depth of the cut, it is possible to analyze the stress field as a depth function for relatively simple stress distributions.

Methods of measuring residual stresses by refraction

In the general case, the refraction condition, which is the working principle of methods for measuring residual stresses by refraction, is expressed by Bragg's law:

$$n \cdot \lambda = 2 \cdot d \cdot \sin\theta \qquad (6)$$

where:

λ: the wavelength of the incident beam radiation

θ: the angle between the incident (or reflected) beam and the surface of the reflection planes

d: the distance between the reflection planes, and

n: the class of reflection (n=1, 2, 3...).

Electron beam diffraction measurement

The electron beam is used to examine very thin objects (under 100nm thickness) and can achieve very high transverse spatial resolution (up to the limits of the grains). Because the method examines very thin objects, the results it gives are vulnerable to surface stress relief effects. Nevertheless, the method provides a way of measuring surface stresses of both I and II types as well as "long" internal stresses in very small electronic components.

X-ray beam refraction measurement

Laboratory X-rays (wavelengths between 0.1 and 0.2 nm) typically look at very thin layers of coating (typically some tenths of the micrometer). It provides a significant advantage in techniques that consider the measuring range to be subject to biaxial stress due to internal stresses (σ_{3i}=0 for each i). The technique of measuring residual X-ray stresses (in particular those which distort the crystal structure of the materials, i.e. change of their intramuscular distances) is possible due to the fact that the wavelength of the X-rays is of the same order of magnitude as the intra-atomic distance within the metal crystals. The short wavelength of the X-rays makes it possible to penetrate the crystal lattice by a percentage and reflect them on the grid levels.

Neutron beam diffraction measurement

Like other refraction techniques, neutron beam refraction is based on elastic deformations in a polycrystalline material. Measurements are made in a similar way as in the refraction of X-rays, with a motion detector around the sample that finds the locations of refractory high-intensity rays. The neutron beam provides us with the advantage that, for wavelengths comparable to the atomic space, its penetration into the materials typically reaches up to several centimeters. Thus, by limiting the area radiated and the beam's field of action by means of special fissures or focusing devices, it is possible to obtain a refractive intensity (derived from the beam) derived from a very small volume (below 1 mm^3) located deep inside the sample under consideration. However, compared to other techniques such as X-ray refraction, the cost is much higher and the availability is much lower. At present the main use of the method is mainly in central research centers.

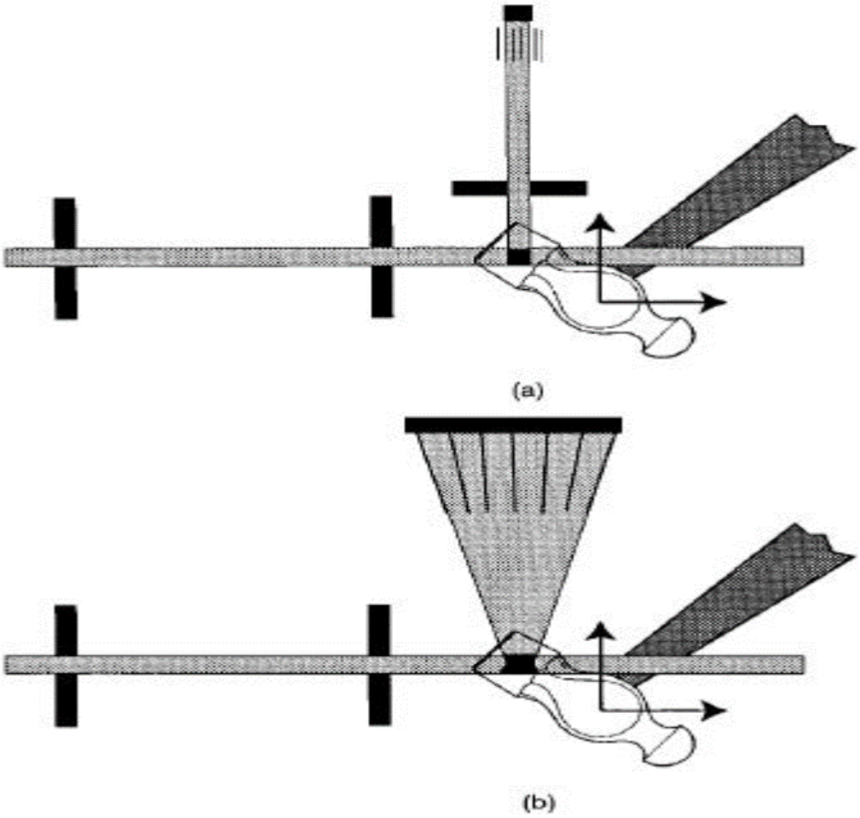


Figure 16: Neutron beam refraction. (a) notches or (b) focus telescopes are used to limit the range of beam vision for small volume measurement deep inside the material. To produce the stress or distortion map, the object is gradually "scanned" through the same volume. Different components of the distortion are measured by rotating the piece in question at appropriate angles

Measurement by refraction of a hard X-ray beam

Hard X-rays are gradually becoming available in several practical applications. Sources of hard X-rays can be up to a million times more intense than conventional sources, and provide high-energy photons that are several thousand times more penetrating than conventional X-rays. This increase in penetrating capacity means that the ‘hard’ X-ray refraction is capable of providing a very large analysis and a three-dimensional map of the distribution of deformations at depths of a few millimeters in mechanical assays. In general little research has been conducted on them to date, but both fast data acquisition time (less than 1sec) and small measuring dimensions (up to 20 μm) have been achieved at sufficient penetration depths (e.g. 50mm in aluminum).

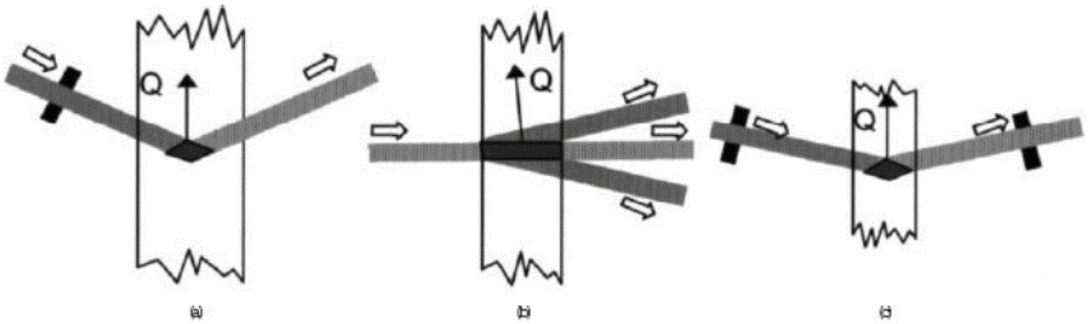


Figure 17: Schematic representation of measurement techniques with "hard" X-rays (a) scanning 2θ (b) beam emission at small angle (c) energy diffusion technique.

Other methods of measuring residual stresses

Magnetic and electrical techniques

The magnetic properties have been used to measure residual stresses and their advantages are that they are non-destructive, cheap, and very simple methods. Steel with ferromagnetic properties, like other ferromagnetic materials, is sensitive to internal stresses due to the interference of magnetism and the resulting magnetoelastic effect. With minimal energy, magnetism will be aligned with the crystalline directions (magnetic axes). A change in stress measure will result in a change in the number of fields aligned with each axis and thus a decrease in magnetoelastic energy. This magnetic anisotropy introduced due to stresses leads to the deflection of an artificial magnetic field from its given direction. A spiral sensor (coil) can perceive these changes in both the direction of stresses and their size.

Another way of "detecting" stresses is MRI. This involves the emission of flexible waves resulting from changes in deformations due to magnetocontraction by changing the position and orientation of the various "regions" of the material. Unfortunately, magnetic methods are sensitive to several factors which need to be taken into account when using methods in experimental procedures. However, for materials that are magnetostrictive, magnetic methods provide cheap methods for non-destructive measurement of residual stresses.

Ultrasonic techniques

Changes in supersonic velocity may be observed when a material is subjected to a stress. These changes provide a means of measuring along the wavelength. The acoustic elastic variables required for the analysis are usually calculated by means of calibration tests. Different kinds of waves can be used, but the most common method is the longitudinal refractory wave method. The greatest sensitivity is obtained when the wave is propagated in the same direction as the stress. The stress is measured by appropriate types as a function of the wave characteristics. The method enables the measurement of "long"-sustained stresses in large volume segments of a material. The velocities of ultrasonic waves depend on inhomogeneous microstructure of materials and difficulties in separating impacts due to multi-axial intensive situations. However, being portable and cheap, the method is suitable for routine inspections and industrial scale studies of large parts.

Thermoelastic processes

Elastic deformation of a material causes small changes in temperature (1 mK for 1 MPa in steels). It is possible, using a suitable infrared camera, to map the temperature changes giving an indicative picture of the stress variations. The temperature change on which the method is based is quite small compared to the sensitivity of the infrared cameras at our disposal, which is why the method has limited use at present.

Photoelastic processes

The speed of light as it passes through transparent materials tends to vary unevenly when the material is subjected to stress. This effect is called photoplasmic and is the basis of another method for measuring residual stresses. These stresses alter the interior of the materials by forming characteristic structures which become visible by the use of white or monochromatic light (assuming materials through which light can pass through). These structures can be "translated" (via appropriate types) and give local stresses once we know the optical constant through calibration experiments. Photoelastic measurements are generally made using models of two-dimensional epoxy resin or very thin slices cut from three-dimensional models in which the stresses have remained "frozen".

Methods for measuring transformations

Techniques for measuring distortions due to phase transformation are based on observations made on free surfaces. A sample of the initial phase of the material is prepared by metallographic methods and then gradually converted to the new phase. The resulting shifts on the free surface give us information about the deformations due to the transformation. The shifts can be measured by the deviation of various reference mark points (such as trenches or grooves) or by using appropriate microscopic methods.

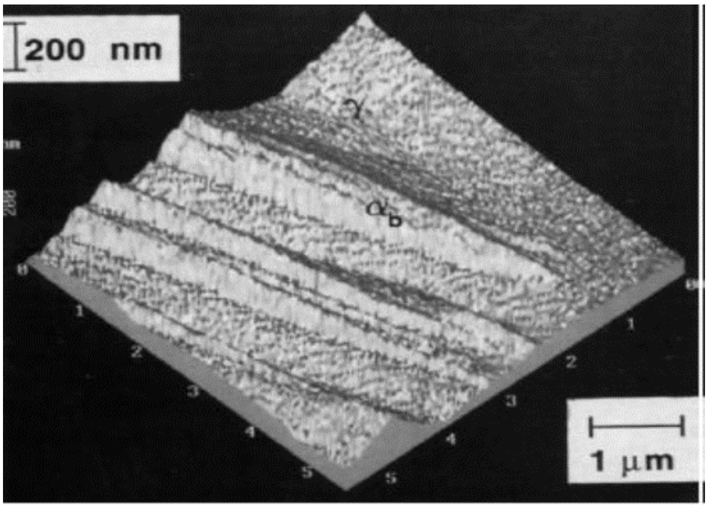


Figure 18: Surface deformations due to phase transformation. Surface etchings visible

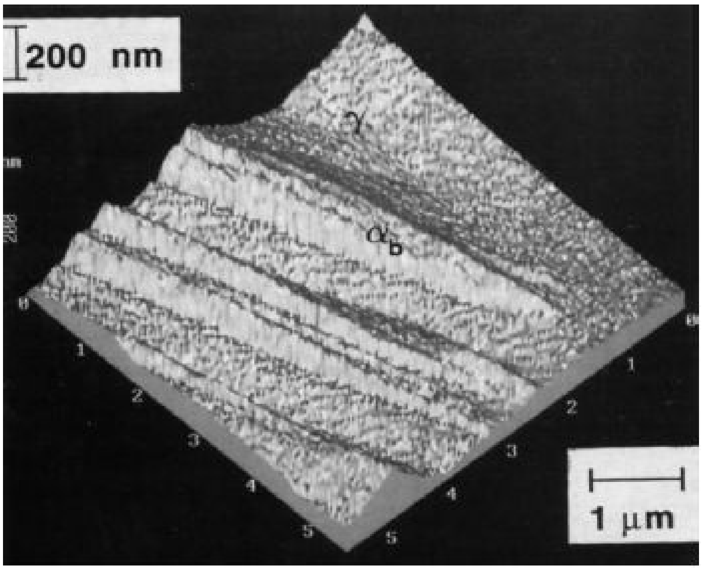


Figure 19: Case requiring greater analysis. An individual microscope is used which illustrates surface tension relief due to the formation of bainite which causes surface shifts

Hole drilling measurement

The most widely used modern method for measuring residual stresses is the bore method. The technique of the method is intended to monitor and measure the change in stresses produced when a hole is made in an element containing (exhibiting) residual stresses. As shown by its technique, it is a method that combines the removal of material and relaxation of the stress under consideration, and can usually be classified as semi-destructive because the hole created is either insignificant or can be subsequently corrected by appropriate procedures which may affect the final field of stress.

During opening of the hole, the variation of deformations can be measured in various ways such as by the method of photoelasticity or by the aid of brittle coatings. The main method which we will use in the experimental procedure is the use of electrical elonsiometers (strain gauges). Then, knowing the measure and direction of the stresses suffered relaxation, the size of the hole and the properties of the material, the remaining stresses can be predicted by classical or empirical analysis. Often, for obvious reasons (large size of the piece in question), blind rather than through holes are opened, but they make it difficult to interpret the residual stresses, as we shall see below. It also usually gradually opens the hole (at various depths) giving us an insight into the variation of the stresses versus depth.

Control and reduction of residual

The general rule in welded constructions is to keep the remaining stresses to their minimum possible values. Achieving this goal can be done in two ways. With proper pre-welding design and post-welding stress relief procedures. The pre-welding design is mainly focused on reducing the volume of the welding metal, since the residual stresses are affected by the contraction of the welding metal during solidification. This can be carried out by properly preparing the edges of the laminates. For example, a U-shaped bevel requires less welding metal than a V-shaped bevel. Also the design should aim at the smallest possible opening dimensions of the connection and at the smaller V angles that allow the electrode to be accessed for welding, so as to minimize welding metal.

The procedures for reducing residual stresses after welding relate mainly to thermal or mechanical effects. The best known method is stress relieving, which involves heating the weld at some temperature. The increase in temperature causes a decrease in the leakage limit of the metal and thus allows the relaxation of the residual stresses through plastic deformation. Redistribution of residual stresses during fouling may cause unwanted bumps in the weld. For these reasons, several times, the defective annealing is carried out, while the plates are fixed to the table where the welding is done.

Residual stresses may also be reduced by mechanical means such as hammer peening, shot peening and vibratory stress relieving, either mechanical or ultrasonic. The latter process utilizes the energy of the elastic waves to redistribute and reduce residual stresses.

Chapter 2

Welding distortions

Welding deformation is defined as the distortion of the component resulting from the expansion and contraction of the welding material and the adjacent base metal during the heating and cooling cycles associated with the welding processes. There are six types of weld warps as shown in Figure 5.1

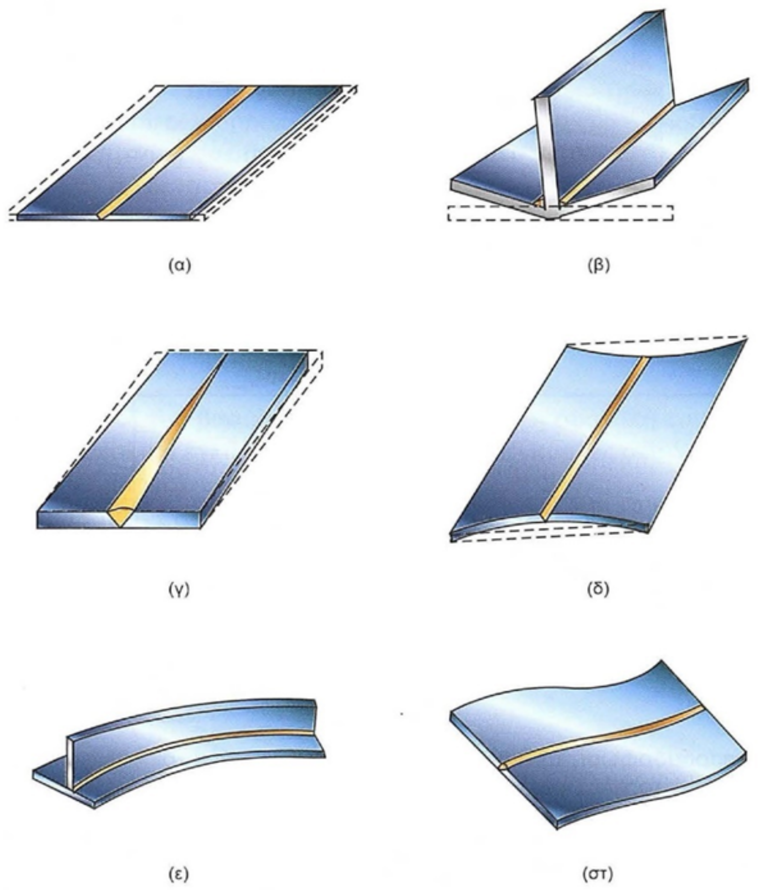


Figure 20: Welding distortion: (a) transverse contraction, (b) planar rotation, (c) angular change, (d) longitudinal contraction, (e) longitudinal bending distortion, (f) buckling distortion

Deformations in welds are classified as follows: (Figure 20)

- Transverse contraction, involves contraction in a direction perpendicular to the axis of welding (Figure 20 a)
- Field rotation, related to transverse contraction and involving rotation in the laminate plane (Figure 20 b)

- Angular change, involving percussion around the welding axis caused by the inconsistent temperature distribution across the thickness of the plate (Figure 20 c)
- Longitudinal contraction, involving contraction along the welding axis (Figure 20 d)
- Longitudinal bending deflection, which is caused by bending in a plane perpendicular to the plate and passing through the welding axis due to the uneven distribution of longitudinal contraction along the welding axis (Figure 20 e)
- Buckling caused by the remaining depressive stresses, most frequently occurring in fine plates (Figure 20 f)

The true deformations of welded structures are more complex than those in Figure 20. However, they can most often be broken down into individual components corresponding to the basic deformations of Figure 20.

Transient distortion of the metal during welding

During the transient distortion of the metal during welding of a rectangular sheet see in figure 21 the deformation as one of its edges is heated by a moving electric arc. The top area of the plate near the thermal source is heated more and expands relative to the lower area. So it bends along the AB curve, where the bending arrow is positive. If all deformations during the thermal cycle· were elastic, then the thermal stresses would be zeroed at the end of the weld and the bending arrow would follow the ABC'Δ' curve. In fact the laminate undergoes plastic deformation in the areas where high temperatures develop and so, after bonding, residual stresses develop. The bending of the plate follows the ABDG curve. After cooling the laminate to its initial temperature, the final deformation is characterized by the final bending arrow, which is now negative. So it seems that the transient deformation during welding and the final deformation after the completion of the welding develop in opposite directions, while they are about the same size. Here it is emphasized that the development of the residual stresses of distortion in welds takes much longer than is required for welding to occur. That is, the residual stresses and distortions continue to develop during cooling of the plate and take their final values only when the plate cools to its original temperature

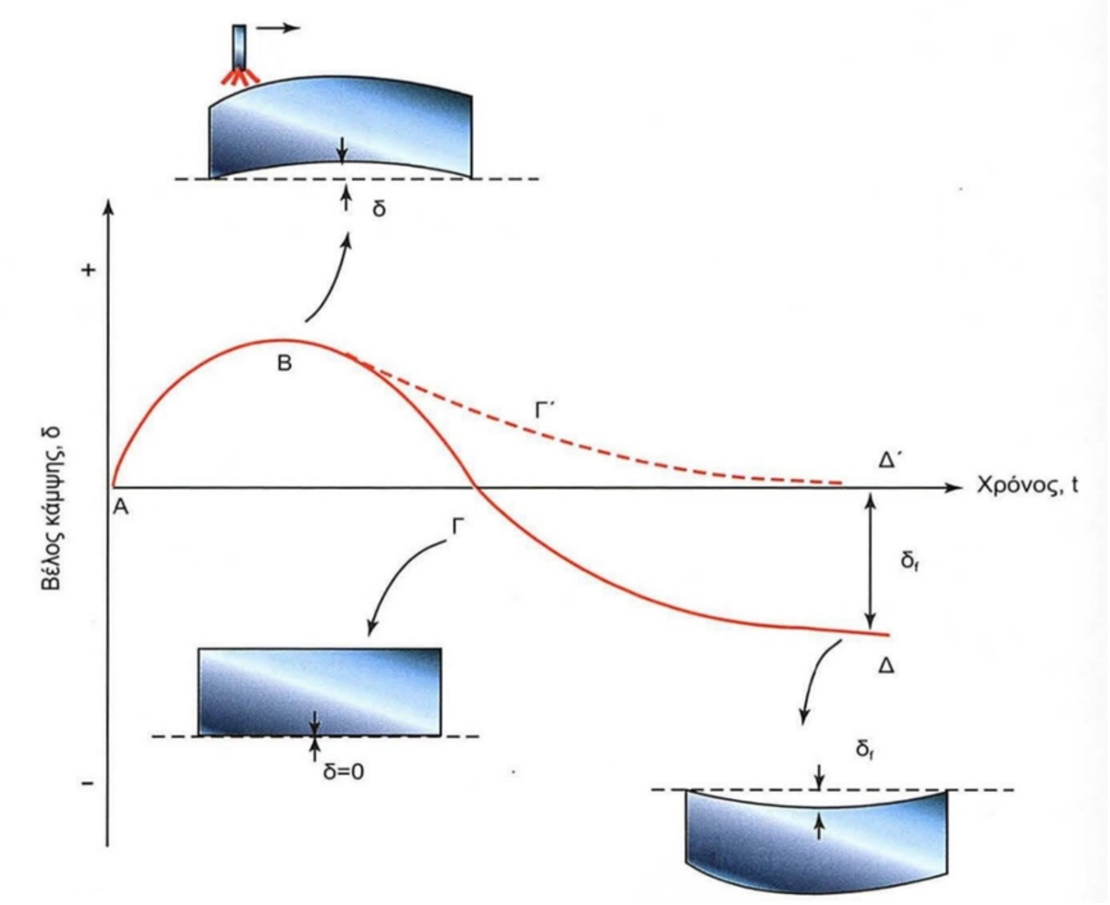


Figure 21: Transient deformation of rectangular plate during heating of the upper edge of the electric arc

Another interesting point is that the transient deformation is greater when the welding axis is away from the neutral axis, and greater bending moment develops. From the above analysis it appears that most of the non-elastic deformations, which cause the residual stresses and deformations of welded structures are produced during welding, meaning that for the effective control of both residual stresses and deformations it is preferable to take action during welding (pre-tension, fixing) rather than taking action after performing welding (direction by heating).

Transverse contraction

The transverse contraction of welds consists of two components: the thermal contraction of the base metal near welding and contraction of the welding metal. Figure 22 shows the mechanism of transverse contraction in a free junction weld with a pass (free bonding is the one in which no external constraints are imposed, such as laminating) The heat flowing to the base metal forces it to dilate. This expansion is obtained from the metal that is contracted due to its solidification. Thus during welding ($t=t_s$) the expansion of the base metal is balanced by the contraction of the welding metal, then the total transverse contraction of the sheet is S=0 and the ends of the sheet A and A` are not moved. At time t>ts the base metal is cooled and contracted by $S_{BM}$ the welding metal, which has in the meantime solidified is contracted by $S_{WM}$ while resisting the further contraction of the base metal. This causes the movement of the ends of the A and A` laminates. The overall transverse contraction is:

$$S = S_{BM} + S_{WM} \qquad (7)$$

Where

S_{BM} is the contraction of the base metal and

S_{WM} is the contraction of welding metal.

The total transverse contraction is mainly due to S_{BM}. The S_{WM} makes up only 10% of the S. If the contraction of the welding metal is ignored and in addition the thermal expansion coefficient is considered independent of temperature, then the transverse contraction in welds confluence of thin sheets (in a fold) is:

$$S = \frac{\alpha_T \cdot h}{\rho \cdot c \cdot H} \cdot erf\left(\beta_s\right) \qquad (8)$$

$$\beta_s = \frac{W}{4 \cdot \pi \cdot \alpha \cdot t_s} \qquad (9)$$

Where

T the thermal expansion coefficient, h the heat input rate (REV), C the specific heat, if the heat diffusion, ρ the density, H the sheet thickness, W the total welding width and t_s the welding integration time

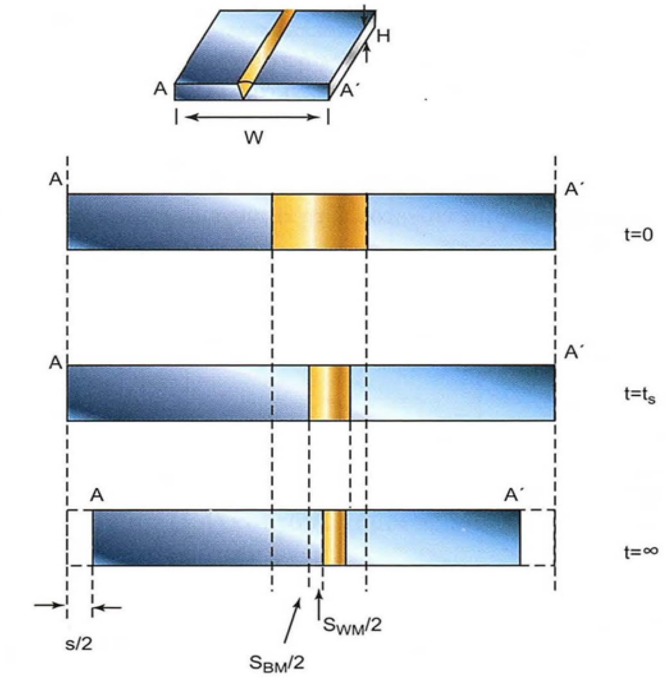


Figure 22: Development of transverse contraction in welds

From the ratio (8) it appears that the transverse contraction decreases with the increase of the thickness of the laminate. Of course the ratio (2) applies to welding on a fold. If more than one pass is required for welding of a plate, then the transverse contraction will be greater. Ratio (2) indicates that in aluminum welds the transverse contraction is greater than in steel welds, since aluminum has a higher coefficient of thermal expansion. Another important factor affecting transverse contraction is the heat input rate (REV). An increase in REV causes an increase in transverse contraction. Experimental results from measurements of transverse contraction in welds are in the form of the curves in Figure 23. These curves show the change in transverse contraction versus time for two thick plates. The time ts is the time required to complete the welding of length L. Figure 23 shows that most of the transverse contraction develops after the end of the weld and when the laminate is cooled.

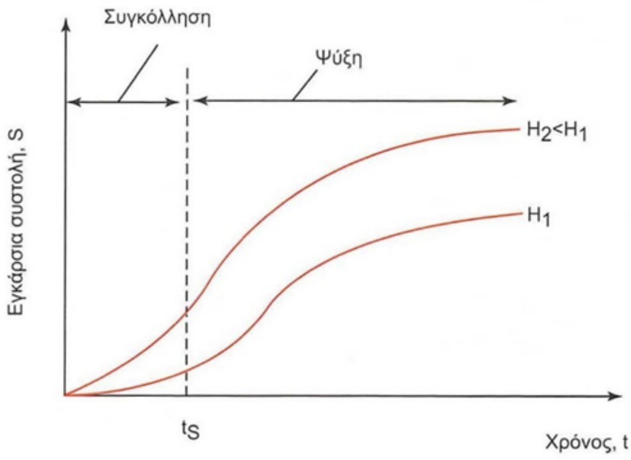


Figure 23: The change in transverse contraction (S) by the change in weight of the deposited metal (w)

Effect of welding metal-multiple

Multipass welds and transverse contraction increases with the amount or weight of the metal deposited. This metal comes either from the electrode or from the welding wire. As a parameter, the quantity of welding metal deposited contains and the amount of heat introduced into the metal, because to deposit more metal required more heat. Figure 24a shows that the transverse contraction increases with the weight of the welding metal, which is expressed with the parameter w (in gr/cm). The w is increased by successive passes deposited in the weld. However, it seems that the transverse contraction does not increase at a constant rate, but that with the increase of passes the increase of S is slower this is due to the constraint imposed on the welding of previous passes. If the data are placed in a S-logw diagram. (Figure 24b) then a straight line is obtained, described by the relation:

$$S = S_0 + b\left(\log w - \log w_0\right) \qquad (10)$$

Where S_0 and w_0 are respectively the transverse contraction and the weight of the welding metal after the first pass, while b is a coefficient.

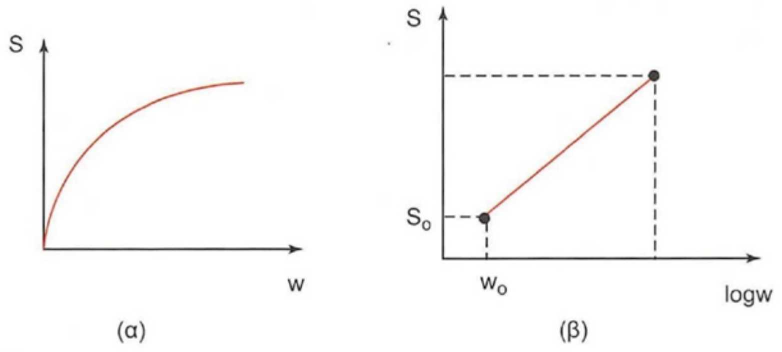


Figure 24: The change in transverse contraction (S) by the change in the weight of deposited metal (w)

On the basis of the above, the factors that affect transverse contraction are:

- Welding root opening
- Shaping edges with milling
- Electrode size

Transverse contraction increases with increasing root opening, as this increases the amount of metal deposited. The effect is large and corresponds to the effects (1) and (2) of figure 25. For connection geometry, single V welds are accompanied by a greater transverse contraction than double V welds. The effect is large and corresponds to the effects (1) and (2) above. This is because in single V welds deposited more metal the same sheet thickness. With regard to the size of the electrode (or the diameter of the wire) it appears that if a larger electrode is used in the first pass, then the transverse contraction decreases. The effect is modest and corresponds to the effect above.

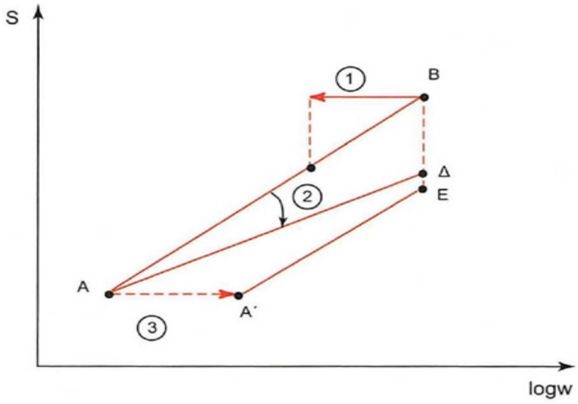


Figure 25: Effects to reduce transverse contraction in welds. 1: reduction of deposited metal, 2: b tilt reduction, 3: metal weight gain in step 1

Effect of the welding sequence

Here we will refer to the order in which a welding of a specific length is carried out, as it affects the deformations of welds. First of all, it affects transverse contraction. We consider two sequences (Figure 26a):

- Weld to parts
- Continuous welding

Both sequences are performed with multiple passes in case the thickness of the plate requires it. We divide the first case into three sections 1, 2 and 3. After the weld is completed in one section then we weld the next section by the same procedure, and finally section 3. In the second case, the welding is done continuously from left to right with one pass each time in the same always conditions. Figure 26b shows that section weld results in less transverse contraction than continuous and is due to the fact that section weld produces milder temperature gradients than continuous welding.

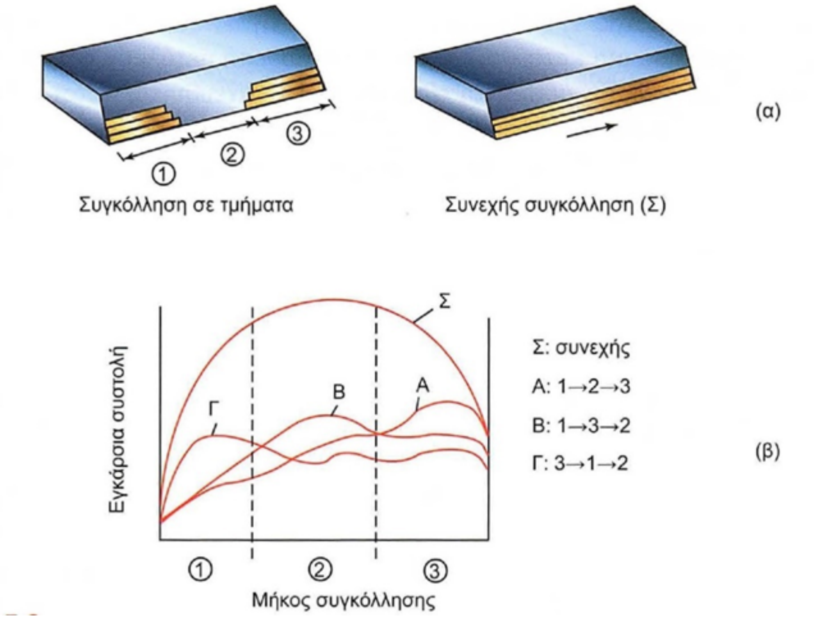


Figure 26: Effect of welding sequence on transverse contraction

Angular change in frontal variations

Angular change is one of the most important and most undesirable deformations of welded structures. The angular change (Figure 27) occurs due to the uneven distribution of transverse contraction in the direction of the thickness of the laminate resulting in out of plane in the construction. The difference of transverse contraction in free welding (Figure 27a) causes the plate to rotate around the welding axis (Figure 27b)

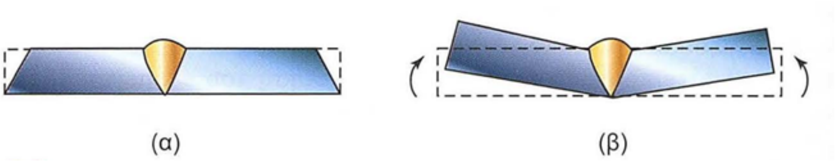


Figure 27:Angular change: Non uniform transverse contraction (a) causes the angular change(b)

In very fine plates, the angular change is very small because there is no difference in transverse contraction. Single or double V welds are used in thicker sheets. In the case of single V, a larger angular change is caused than in double V, the angular change being dependent on the deposit of the amount of metal on the top surface relative to the bottom surface as it first causes an angular change in one direction and then in the opposite direction when deposited on the bottom surface. Thus the angular change is dependent on the ratio h_1/h_2 (Figure 28) and in addition there is a thickness of plate for which the ratio h_1/h_2 minimizes the angular change

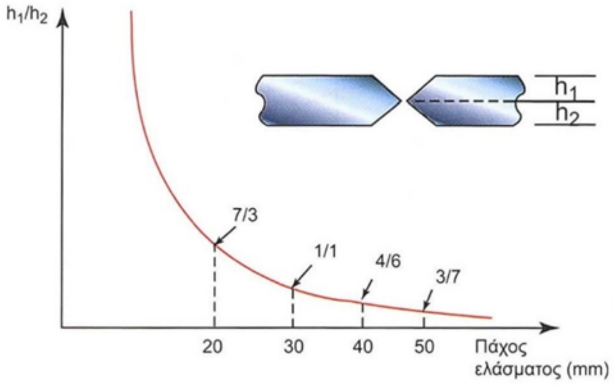


Figure 28:Weld edge configuration to achieve minimum angular change

Angular change in cervical welds

Many cases of welded structures are reinforced by laminates consisting of transverse and longitudinal welds which are cervical. One of the biggest problems of these constructions is the off-level deformations, due to the angular change of the cervical welds (Figure 29). Special emphasis on this problem is caused by thin laminates of light constructions.

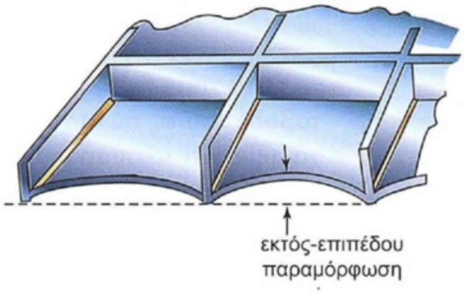


Figure 29:Out-of-plane distortions

In free cervical welds, the angular change causes local bending at the junction points, resulting in the construction taking the shape of a polygon (Figure 30a). By welding in the construction of cross-sections of a sturdy beam (Figure 30b), then the angular change of welds will cause a bending of the sections of the bottom plate between the welds and the laminate will acquire a corrugated form. This condition is characterized by significant out of level deformations, which reduce the strength of the reinforced laminate to buckle. The angular change in the cervical welds, as in the confluence welds, is caused by the uneven distribution of transverse contraction in the direction of the thickness of the sheet, due to the uneven temperature distribution in the thickness, because the top surface of the sheet is heated more than the bottom surface. Free cervical welds (without external constraints) are characterized by the angular change φ_0 (Figure 30a). When the connection is contained, the angular change φ becomes smaller (Figure 30b)

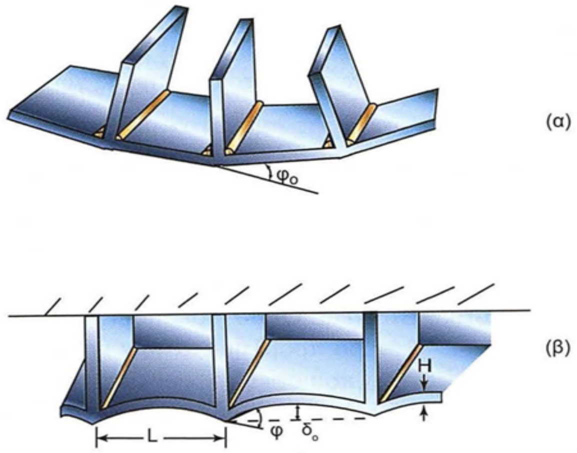


Figure 30:Angular change in cervical welds: (a) free welds, (b) welds with external restriction

In Figure 31 we observe the qualitative change of φ_0 in cervical welds of steel and aluminum as a function of the thickness of the sheet and the amount of deposition of the metal, with the thickness being specific, H_0 for both materials, to the point where the angular change becomes maximum. The thickness H_0 depends on the geometry of the connection and welding conditions . In laminates less than H_0 thick, the angular change is small. This is due to the fact that there is a more uniform temperature distribution during the thickness of the laminate. With a thickness greater than H_0, the angular change decreases because the plate rigidity increases due to its thickness. Regarding the variation φ_0 it seems to become steeper in steel than aluminum depending on the thickness of the laminate This is because aluminum has a greater conductivity coefficient.

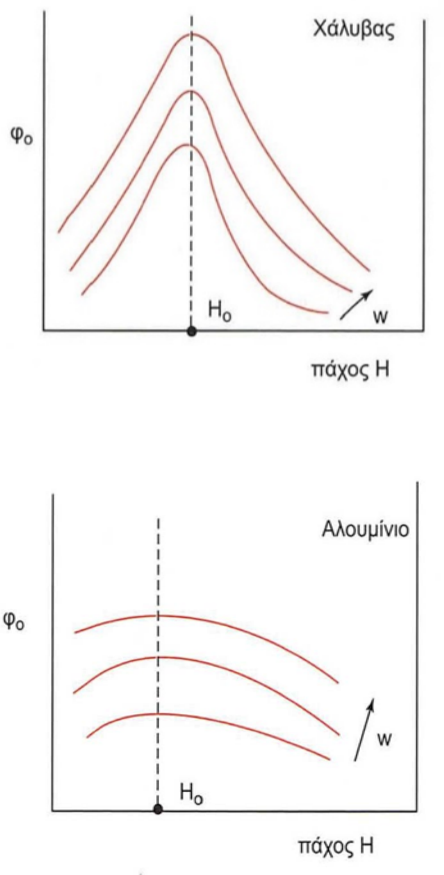


Figure 31:Change in angle φ0 depending on the thickness of the plate

In confined cervical welds the angular change φ_0 is less than φ_0 and causes the plate to bend between the connections. This bending is characterized by a bending arrow d_0 in the middle of. In Figure 32, the qualitative change of δ_0 in the cervical welds of steel and aluminum is observed in relation to the size of the cervical weld D_f (which is proportional to the amount of deposition of the metal) and the opening B between welds. The bending arrow is larger in the welds than in the aluminum, while increasing with the size of the cervical weld D_f due to the increase in the deposition metal. In this case the bending arrow is increased with the opening length B. For 6 to 18mm plate thicknesses and 0.5 to 0,8mm openings, both steel and aluminum have a bending arrow ranging from 2 to 8mm depending on the size of the cervical weld. The resulting deformation is significant and out of the permissible limits most often. Therefore, deformation before welding should be reduced by applying the following when drawing welds:

- Avoid over-dimensioning of cervical welds
- Proper selection of heat input rate (i.e. welding conditions) to prevent unwanted heat input into the connection
- Suitable welding sequence
- Preheating
- Elastic pre-tension

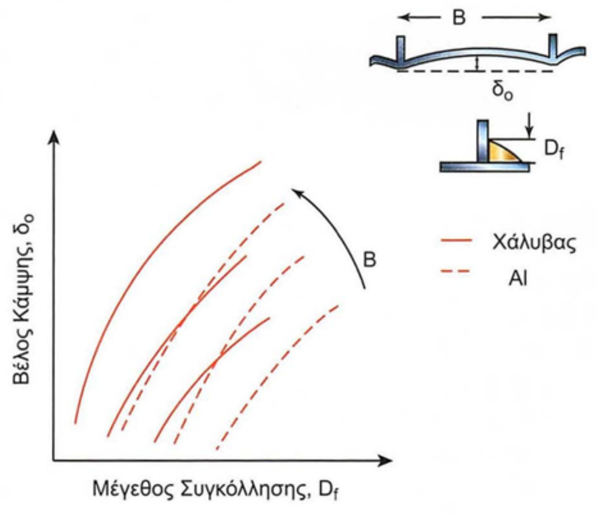


Figure 32:Bending arrow change δ0 depending on cervical weld size

In the case where we preheat the bottom surface of the laminate the deformation is reduced due to the fact that we have a uniform temperature distribution in the thickness of the laminate compared to the case that we do not have preheating as shown in Figure 33

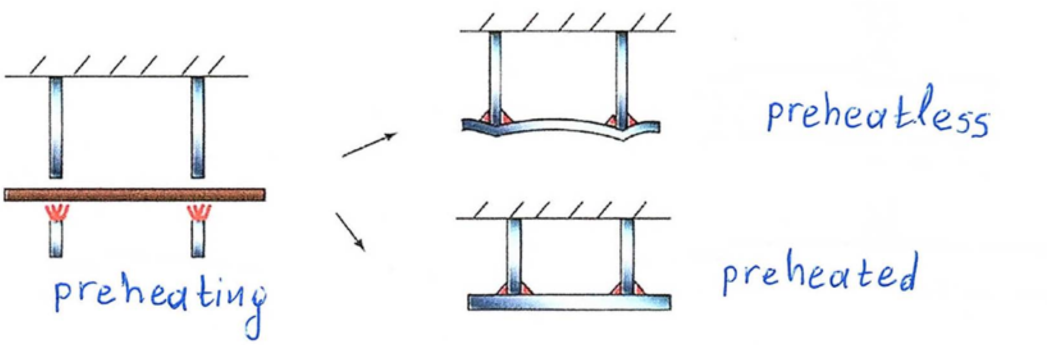


Figure 33:Decrease in angular change by preheating

In the case of an elastic pre-intensity in a direction opposite to that of the angular change there appears to be a reduction of the deformation as shown in Figure 34. The elastic pre-tension shall be carried out with appropriate restraint on the table to be welded.

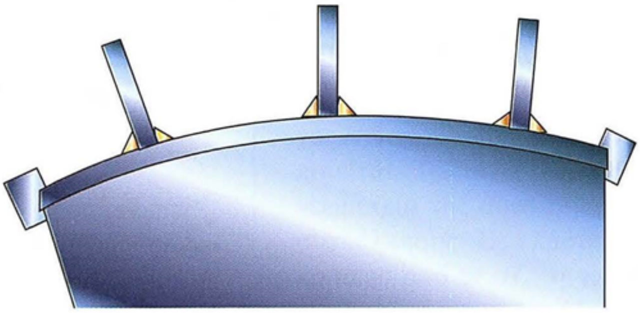


Figure 34:Decrease of angular change with elastic pre-stress

Longitudinal contraction and longitudinal flexural distortion

The longitudinal contraction is much smaller than the transverse one and occurs in both junction welds and cervical welds, and is of the order of 1/1000 which means 1mm per meter of weld. Of particular importance in this case is the longitudinal bending distortion caused by the weld in cross sections of T or I long beams and not the longitudinal contraction as shown in Figure 35. In this deformation when the axis of welding does not coincide with the neutral axis of the beam, it is more pronounced and caused by the bending moment developed by the longitudinal contraction.

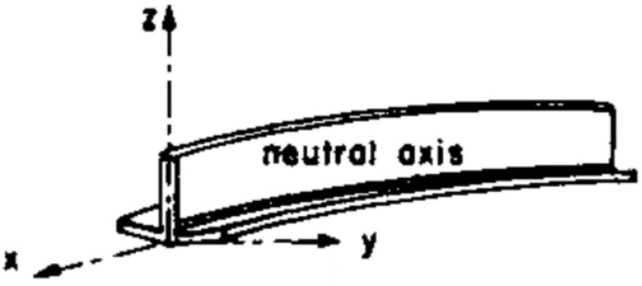


Figure 35:Longitudinal bending distortion in welded bars

In the next Figure 36 we observe that when welding of the lower tread on the I beams the deformation increases as the number of passes increases, on the beams However, when welding and the upper tread is done we have a reduction of the deformation. In the case where equal amounts of metal are deposited on both the upper and the lower tread, the flexural deflection shall not be zeroed but shall remain at least a small one as shown in point C. This means that the deformation caused by the welding of the upper tread (B) is less and due to the rigidity of the beam due to the welding of the lower tread. In the case of T beams, the amount of metal deposited increases and the flexural deformation. When welding aluminum beams the deformation from the effect of the material is less than that in the case of welding steel beams. This is due to the uniform temperature distribution on the z axis of Figure 35.

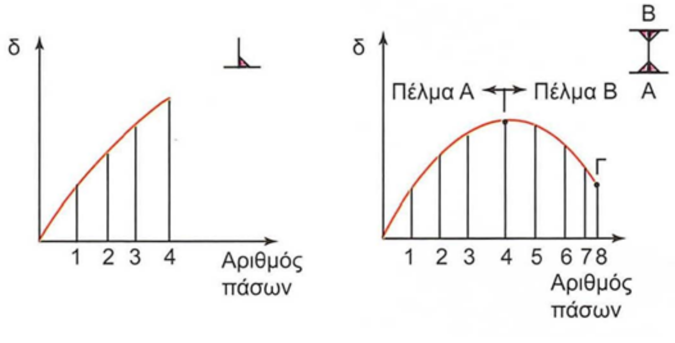


Figure 36:Bending arrow change according to the number of passes in welded beams

In the case that the beams are constructed by intermittent welding as shown in Figure 37 no longitudinal bending deformation is developed perhaps because no significant longitudinal residual stresses are developed due to the short length of the individual segments.

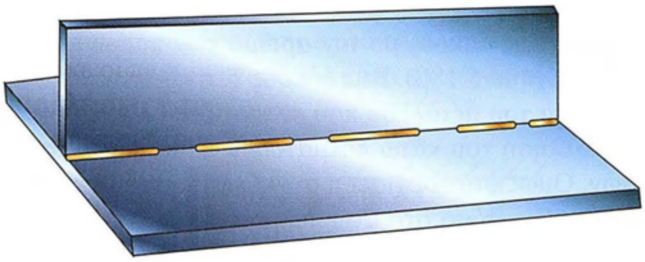


Figure 37:Beam intermittent weld

Buckling distortions

The residual stresses in the welds are tensile near the weld seam and compressive in areas far from the seam (Figure 38a). In fine plates the compressive stresses can cause buckling (Figure 38b). Buckling deformations differ from the out-of-plane distortions caused by the angular change of welds, mainly in that buckling distortions are much larger. Also, the welded laminate, which undergoes buckling, can get more than one shape after buckling distortion. Buckling distortion problem is the appropriate choice of welding conditions (Heat Input Setting), laminar thickness and weld distance. After conducting experiments on buckling distortion showed that buckling distortion is not strongly dependent on the welding method and that buckling occurs when the J parameter exceeds the critical J_{cr} value:

$$J = \frac{h}{H^3} B \qquad (10)$$

Where h the heat input rate in J/mm, B the distance of the reinforcing elements and H the thickness of the plate in mm. The price of J_{cr} is 1.6 KJ/mm^3 for steel welds. In Figure 39 we observe the buckling distortion δ/H in the middle of the plate as a function of the parameter J. In the case of $J>J_{cr}$ the bending deformation increases sharply

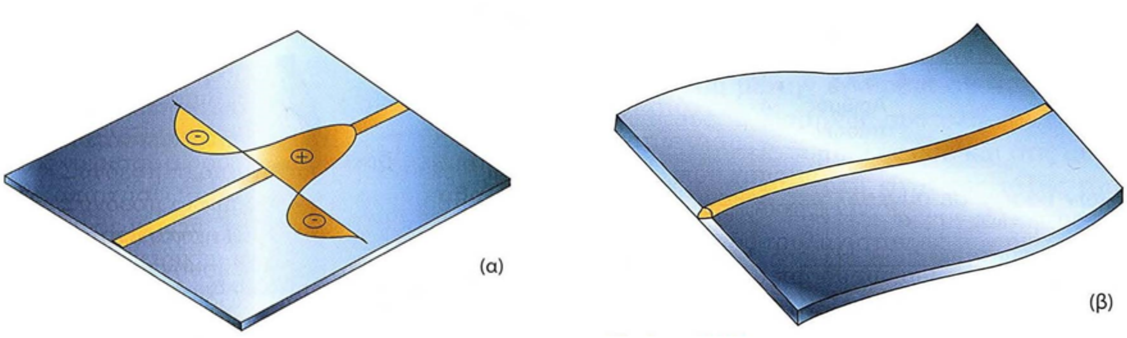


Figure 38:Compressive stresses (a) causes buckling distortions (b)

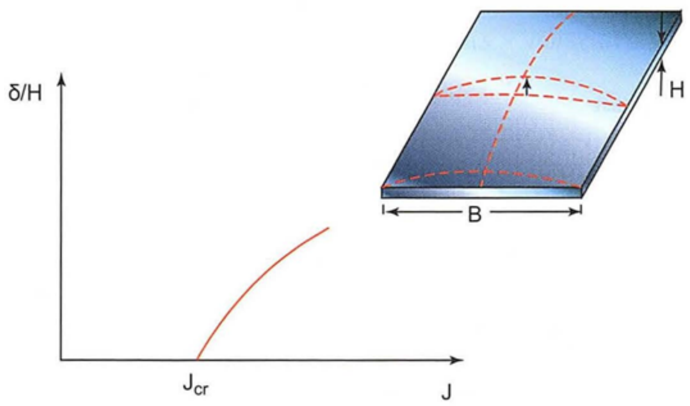


Figure 39:Buckling distortion at the center of the plate (δ/H) versus J parameter

Control of distortions in welds

In the following paragraphs, methods and procedures for limiting deformations in welded structures will be discussed. First the methods adopted during the design stage will be mentioned and then the deformation processes after the end of welds in a construction will be described.

Control of distortions during design stage

The most important parameters that affect the deformations are the thickness of the laminates, the configuration of the edges, the welding sequence, the welding conditions, the amount of welding metal, as well as the mechanical constraints imposed by holding the laminates.

Sheet thickness

The thickness of the plate affects as mentioned above two types of deformations, the angular change and the buckling deformation. In figure 31 is shown the effect of thickness on the angular change. There seems to be some critical thickness H_0 where the angular change is maximized. Therefore, it could be chosen smaller or thicker than H_0 to cause small angular change. In the case that less thickness is chosen (which is intended in light constructions) care should be taken to avoid creating problems with buckling deformations. As mentioned above, buckling is caused by the depressive remaining stresses in thin sheets. Figure 39 shows that there is some critical thickness, under which the buckling deformations get large values. Therefore, in the case that a smaller sheet thickness should be chosen to limit the angular change, parallel measures should be taken to limit the buckling deformation, such as an appropriate choice of welding conditions, spacing of reinforcing elements, etc.

The configuration of the edges

The configuration of the edges affects the deformation of welds since it affects the amount of metal deposited during welding. Here the general rule is that a configuration should be chosen ("milling") that minimizes as much as possible the deposited metal.

Welding conditions

Transverse contraction increases with the amount of metal deposited in a weld. This is because it increases the total amount of heat introduced into the weld. Heat input rate affects many types of distortion, such as angular change and buckling distortions. A general rule is therefore that welds are made at the lowest possible rate of heat input to reduce deformation. This rule includes the selection of the appropriate welding method. In cases where deformations are a main design criterion it may be necessary to prefer a more advanced welding method (e.g. electron beam welding or laser), characterized by a lower rate of heat input than conventional welds. The deformations of welds can be reduced by appropriate retention of the laminates. In most cases this method has a corresponding increase in the residual stresses.

Welding sequence

The weld sequence affects the way temperature fields develop and thus affects the deformations of welds. Also the welding sequence imposes mechanical constraints, because the preceding welds increase the robustness of the structure to deformation caused by the following welds. A general rule concerning the welding sequence is that welds start the center of the construction and proceed to the ends, as shown in Figure 40 when welding reinforcements on flat plate. We have also seen that transverse contraction decreases when welding in segments is preferred to continuous welding and that transverse contraction in multi-pass welds can be reduced when using a larger electrode in the first pass.

As far as it concerns the longitudinal buckling deformation of beams T and H, it has been stated that the deformations are reduced by using intermittent rather than continuous welds (Figure 38).

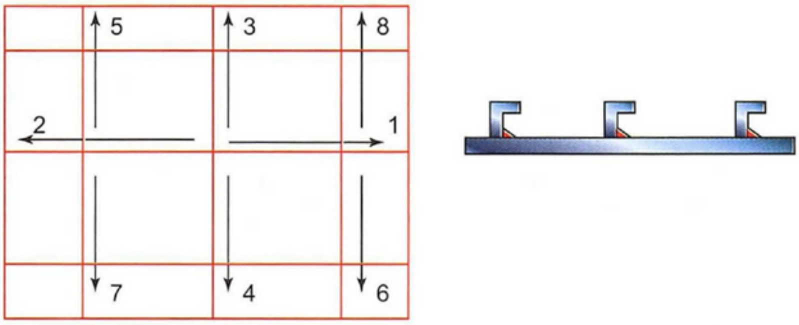


Figure 40:Center-to-edge welding sequence to constrain distortions.

Pretension and preheating

With the appropriate pre-tension or preheating the angular change in cervical welds can be reduced.The general rule is that pre-stress can lead to a reduction in deformities, but it leads in most cases to an increase in the residual stresses. For these reasons it should only be done after proper planning.

Reduction of distortions after welding

The procedures followed to reduce deformation after welding include mainly the direction by heating (flame heating), which can take various forms, as shown in Figure 41.

- Linear heating: It is mainly used to reduce angular change in cervical welds.
- Spot heating: It is used to reduce deformation in thin films.
- Pine needle heating (cross directions): Due to heating in two directions it results in a more uniform reduction of deformations.
- Frame heating: Used to reduce large distortions.
- Triangular heating: It is used to reduce longitudinal bending deformation in welded beams.

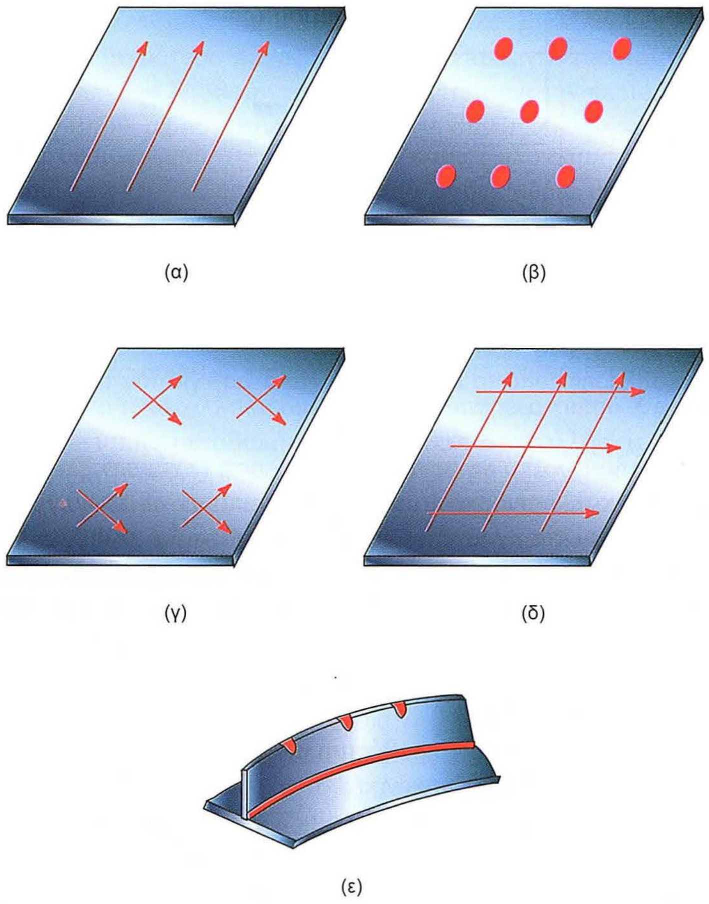


Figure 41:Various types of directions by heating (a) linear heating (b) pine needle heating (c) pine needle heating (cross directions) (d) frame heating and (e) triangular heating

Bibliography

1. Δημήτρης Ι. Παντελής, Β. Ι. (2017). *Επιστήμη και τεχνολογία των συγκολλήσεων.*
2. Barsoum, Z. (2008). Residual stress analysis and fatigue of multi-pass welded tubular structures. Engineering failure analysis, 15(7), 863-874.
3. Cordeiro, F. D. S. (2015). A critical analysis on welds distortion (Doctoral dissertation, Universidade de Coimbra).
4. James, M. R. (1992). Application of X-Ray Residual Stress Measurements in Industrial R&D. In Measurement of Residual and Applied Stress Using Neutron Diffraction (pp. 37-50). Springer, Dordrecht.
5. Masubuchi, K. (2013). Analysis of welded structures: residual stresses, distortion, and their consequences (Vol. 33). Elsevier.
6. Michaleris, P., Dantzig, J., & Tortorelli, D. (1999). Minimization of welding residual stress and distortion in large structures. WELDING JOURNAL-NEW YORK-, 78, 361-s.
7. Paranjpe, A. (2014). Residual stresses in machined titanium (Ti-6A1-4V) alloys. The University of Utah.
8. Prevéy, P., & Hornbach, D. (2015). Residual stress in pipelines. Oil and Gas Pipelines: Integrity and Safety Handbook, Edited by RW Revie, Wiley, Hoboken, NJ, 73-97.
9. Ren, Y. (2018). Investigation of residual stresses in X65 narrow-gap pipe girth welds (Doctoral dissertation, Brunel University London).
10. Stamenković, D., & Vasović, I. (2009). Finite element analysis of residual stress in butt welding two similar plates. Scientific technical review, 59(1), 57-60.

11. Κατσαώρας, Ι. Ν. (2009). Αριθμητική και πειραματική μελέτη των παραμενουσών τάσεων κατά την συγκόλληση χαλύβων (Bachelor's thesis).
12. Venkatesan, V. Kaila Kesavan, Arumugam Murugan &.
13. Sivakumara, J., Jinub, G. R., & Kumaresanc, D. (2013). Analysis of residual stress and distortion. International Journal of Engineering Research & Technology, 2(10), 1610-17

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