Chapter

# Welding Residual Stresses to the Electric Arc

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## Abstract

Arc welding processes are widely used in the industrial sector, mainly for productivity and continuity. However, these processes have several undesirable results, such as distortions and residual stresses (RS). When compared to other welding processes, the RS level can make the welded joint unfeasible. Many studies on these arc welding discontinuities have been carried out in experimental and numerical areas about their measurement, analysis, and control, however, not yet clearly enlightened, since it is a complex topic, both for industry and academia, needing to be deepened. This study aims to present a contextualized approach to destructive and non-destructive techniques used to measure RS generated by arc welding, as well as the influence of these distortions and stresses on the welded structures and, finally, to present possible control techniques. Finally, this study highlights the use of CW-GMAW welding, which achieved a reduction in stress and distortion levels, due to the introduction of a non-energized wire in the arc of the GMAW process, as evidenced by the results of RS measured by X-ray diffraction (XRD) and acoustic birefringence (AB). Thus, in this context, the approach to RS in arc welding presented here is extremely relevant for researchers involved with the topic.


**Keywords:** arc welding, welding residual stresses, acoustic birefringence, CW-GMAW, NDT



## 1. Introduction

The search for improvements in the control of residual stresses resulting from arc welding processes has been intense due to the production requirements imposed by the industrial sector, referring to the fact that stresses affect the mechanical properties of materials, such as strength, plasticity and surface integrity, therefore it is extremely important to measure and evaluate the levels of these stresses in welded joints. The RS exist in structures, parts, components from different manufacturing processes, resulting from interactions of temperature, stresses, and microstructure, which makes its evaluation quite complex. Among the numerous manufacturing processes, the arc welding process generates high levels of RS, formed by the thermal changes imposed. The control of the RS continues from the moment of the conception of the project, passing through the choice of the construction procedures until its completion. There are several ways to measure RS, which can be computational or experimental. During the research of this work it was observed that there is still no standardized system for the distribution of residual stresses, each author uses what suits him, there is no right or wrong way to observe the RS. But a main point can be considered, being the consensus of many authors is the magnitude of the RS, whether it is compressive or tensile, each type of stress has a specific attribute, which may be beneficial or not for the evaluated component. A methodology worth mentioning for the evaluation of RS is the ultrasonic technique of acoustic birefringence (AB), with this technique it is possible to evaluate a metallic component in a non-destructive and entirety. This line of research, presents an interesting approach, but not much explored. The use of different RS measurement and control technologies, widen the options for existing assessment, with the combination of these technologies it is possible to achieve a reduction in RS levels or even almost its complete elimination. Countless welding processes have been used to control RS. Recently a process has been introduced, the CW-GMAW process (Cold Wire—Gas Metal Arc Welding), showing promising results. The premise of the process is to reduce the temperature of the fusion arc/weld pool. In this context, this work addresses a review of the concepts of residual stresses generated by arc welding, as well as their magnitude and implications for welded structures. However, ways of measuring them are also explored, so that more efficient control methodologies, welding processes are developed, which together with the welding procedures, promote significant results in reducing the values of residual stresses and deformations generated.

## 2. Mechanisms for generating residual stresses in electric arc welding

The importance of this study is based on the principle that the most widespread concept of residual stresses (RS) refers to stresses that remain in the component even though the external forces applied on the body are removed [1]. Otherwise, residual stresses are those that are not necessary to maintain the balance between the body and its environment [2].

The state of stresses causes a residual deformation that is self-balancing and, therefore, the resulting forces and moments that tend to zero [Eqs. (1) and (2)]. These equations describe the state of residual stresses considering a generic volume of the material and the moment of the forces acting on the material, respectively. Here, dV is the volume and dM is the resulting moment.

Mainly regarding metallic materials, residual stresses are a consequence of the interactions between time/temperature, stress/strain, and microstructure, that is, residual stresses arise from misfits *(eigentrains)* between different regions or different phases within the material, or even in different layers of atomic arrangements [3].

The material or characteristics related to this that influence the development of residual stresses include thermal conductivity, calorific capacity, thermal expansivity, modulus of elasticity and Poisson coefficient, thermodynamics and kinetics of transformations, transformation mechanisms and transformation plasticity [3].

$$\int \sigma . dV = 0 \tag{1}$$

$$\int dM = 0 \tag{2}$$

The RS are present in all materials that go through manufacturing processes, and in general, in metallic materials they are more evident and extremely studied, a fact that is due to the great use of these materials in the industrial one. Thus, in metallic materials, residual stresses are a consequence of the interactions between temperature, heating time, stress-strain, and microstructure, that is, residual stresses arise from mismatches between different regions or different phases within the material, or still, in different layers of atomic arrangements [3]. Regarding the intrinsic characteristics of these materials, which influence the suggestion of RS, there are thermal conductivity, heat capacity, thermal expansiveness, elasticity modulus and Poisson's coefficient, in addition to the thermodynamics and kinetics of transformations, of the mechanisms of transformations and transformation plasticity [3]. Hence, therefore, the importance of studying residual stresses in metallic materials, due to their great generation complexity.

Another important problem surrounding the RS is its classification, and this is not yet well established, however, some of these classifications will be presented below, according to the point of view of some areas [4]:

a. The most common occurs according to the scale to which they self-balance:

- Type I: These are stresses that act on macroscopic scales, involving several adjacent grains of the material, having an almost homogeneous character. Each interference in the balance of forces and moments of a volume containing this type of stresses may change its dimensions.

- Type II: They correspond to the average stresses within each phase, are almost homogeneous in all microscopic areas, of a grain or parts of it in a material and are balanced through enough grains. This type of stress is also known as pseudo-macrostresses [5].

- Type III: They are heterogeneous in the submicroscopic areas of a material, can be caused by accumulations of displacements (variations in interatomic distances) within a grain or elastic stresses around precipitates and are balanced through small parts of a grain.

b. According to their origins, that is, by the causes as they arose [2];

c. Or according to the effect on the behavior of the welded structure [4]

However, it is known that metal components need to go through at least one manufacturing process, even considering current processes, such as additive or more traditional manufacturing such as lamination, casting, forging, machining, thermal sprinkling or welding, each generates its pattern of residual stresses in the product, which is intended to produce [1]. However, few influences or generate high levels of residual stresses as do electric arc welding processes.

Thus, the joining of metallic parts using the electric arc as a heat source brings together many welding processes used on a large scale in the industry. These arc welding processes cause abrupt thermal changes through the local heat source at different scales giving rise to the known residual welding stresses, that is, the consequent mismatch between different parts (base metal—BM, zone affected by heat—HAZ and weld metal—WM), different phases (microstructures) or different regions of the same part (different grains in the HAZ) contributing to their formation [2]. However, the phenomenology of this process is complex and the following phenomena occur almost simultaneously:

1. In the heating occurs the formation of the weld pool (until the weld pool forms the piece heats up a lot, varying for each material) that expands and generates compressive flow from the neighborhood and when the weld pool cool causes

the formation of contraction forces [6]; more particularly, the mass of the heated volume with the restrictive combinations and the contraction of the weld metal originate the thermal stresses.

2. The heat transfer and the flow of the liquid metal generate thermal gradients in the welded joint, besides actively acting in the shape and size of the melting pool, that is, in the volume of liquid metal. The measurement of heat transfer through the cooling rate helps in the prediction of Thermal Stresses (TS) that will affect the level of residual stresses formed in the welded joint.

3. The volume of the liquid metal depends on the interaction of the welding parameters and the displacement of the electric arc that subjects the welded joint to various thermal cycles, can be differentiated when: (a) if the welding process uses only the electric arc to fuse the parts to be joined, i.e. when only the base metal is melted, autogenous welding (e.g. GTAW) or (b) if transfer of molten metal from the consumable occurs, mixing with the molten base metal simultaneously with the movement of the arc, the weld is deposition (SMAW, GMAW, FCAW, SAW, etc.).

4. Thermal stresses are stresses formed during the thermal cycle, both in heating and cooling, not existing in liquid metal; however, these stresses until they reach room temperature become the forms of residual stresses, distortions and/or defects [7].

5. During the solidification of the weld pool, phase transformations occur influencing or not the formation of residual deformations, depending on the chemical composition of the metal alloy, there is less or greater influence on the formation of residual welding stresses [8].

One way to study the mechanism of generation of residual stresses in welded structures beyond experimentation and measurement is based on thermomechanical processes associated with computational mathematics and simulation with specific software. It is possible to obtain satisfactory results that help in the prediction, control and relief of the real state of residual stresses caused in the structure after welding in a qualified manner, that is, to perceive the effect that each factor or parameter alone has on the magnitude of such stresses. The starting principle is based on the models of [9, 10] referring to the effects of the temperature distribution of the heat source during welding and through these models the possible effects on residual stresses originated as proposed by [11, 12].

However, the great predominance of studies today has been consolidated with residual stresses being influenced by four groups of interrelated welding technology parameters.

- ***Welded structure design parameters***: the thickness of the plate or pipes (thin, medium or coarse), joint geometry (butt weld, fillet, double fillet, etc.) and type of chamfer (V, X, K, U, etc.), pass numbers, chemical composition of the base metal and consumable (wire or rod).

- ***Available choice parameters***: Welding processes (autogenous process), such as GTAW or with metal deposition such as GMAW, FCAW, SAW, SMAW, PAW; the mode used for welding (manual, mechanized, automated), etc.

- ***Application parameters of operational techniques***: welding sequence, welding passes (continuous, intermittent, alternating, reverse, tensioning), pre and post heating, structure with or without restrictions.

- ***Primary operating parameters:*** such as I (current), U (voltage), welding speed (mm/s). These are, however, the most used, because they constitute the energy involved and used for metal fusion, its formula is described according to Eq. (3). Known as heat input (Hp), generic term of welding energy, usually in KJ/mm. Which also interfere in the shape and volume of the weld bead.

$$Hp = \eta.\frac{U.I}{\upsilon_s} \tag{3}$$

First, due to the greater constraints of safety criteria, the design of a conscious welded structure currently involves the skills of welding engineers and designers, considering not only the structure itself, but also the prior knowledge of complex interactions between metallurgical phenomena, aspects related to the mechanisms of connections and the mechanical behavior of all materials involved [13]. Where residual stresses, distortions and failures are perceived to be costly and complex control phenomena. Thus, considering that some areas of industrial production, for example, shipbuilding do not all projects quantify the initial welding imperfections explicitly, but these imperfections reduce the strength of the structure, besides being accumulative [14] and dangerous in the case of vessels when in operation.

In a way, the control of welding residual stresses starts from the choice of the type of material to be welded, that is, carbon steel, because it presents a composition basically formed by Fe and C and few alloying elements that interfere in phase transformations, it is considered in practice that this mechanism has negligible participation in the generation of RS in the weld metal of this type of material. Unlike medium and high alloy steels, stainless steel, Monel, Stellite, etc. these will have their inherent stress levels affected by chemical composition [15]. Thus, welding processes were developed through the formulation and manufacture of special consumables produced with this objective based on the principle of phase transformations at low temperatures (LTTW—low temperature transformation welding), where compressive residual stress formations and distortion reduction are induced [16, 17]. Other characteristics intrinsic to the material such as physicochemical properties (thermal conductivity, thermal expansion, density, specific heat, etc.), may favor for the generation or need preheating to relieve RS, such as copper and aluminum and their alloys, because they are good heat conductors, dissipate it quickly, most often requiring more intense localized sources, due to the difficulty for local fusion of the weld.

Other factors, very relevant that are correlated to the formation or increase of RS in welded components, refer to the parameters of joint geometry such as thickness (plate, pipes, flanges, etc.), type and angle of bevel. The temperature gradient is what differentiates the origin of residual stresses into a thin and coarse component. Where, in thin thicknesses, the weld pool can be considered 2D and in thick thicknesses, 3D, changing the process of heat transfer of the part and, consequently, the distribution of temperature that directly influences the process of RS formation [18]. The geometry of the joint in the form of butt weld, fillet weld, superimposed, among others also affects this distribution, by the way the heat is distributed, being the T-joint is the one with the highest heat removal coefficient [19].

Using models through the application of finite element methods (FEM) applied to the butt weld, with the decrease in thickness the RS increase [20]. A possible argument to describe the fact is that the absorption energy per unit of volume in thin plates is higher than in the thick ones, causing the inverse relationship between the thickness of the plate and the residual stresses. However, in T-joint welds, with the increase in plate thickness, the non-uniformity of the temperature alters the thermal expansion and the contraction during cooling, consequently, increases the RS. In this same type of joint, the increase in flange thickness strengthens the internal restriction by increasing these stresses in T joints [21]. The number of passes also influences the distribution of residual stresses, in fillet weld in T joint, a single pass on one side generates more stresses than when welding both sides [22]. The measurement of stresses at each weld pass was simulated in a joint containing six passes in plates of 16 mm thick hardened steel, where it was observed that the first 3 passes tend to generate more compressive stresses and the following passes 4, 5 and 6 showed the tendency to tensile stresses.

The choice of process also affects the magnitude of RS of electric arc welding, one of the studies that most involves processes with this type of local source, used four of these processes (SAW, DC GMAW, GMAW pulsed and CMT Fronius) and two more laser (one autogenous and one hybrid) applying in naval carbon steel (ASTM A131), where it was observed that the processes showed very similar peaks (near to 400 MPa) proportional to temperature peaks, differing by the width of the peaks, where the SAW has wider peaks [10]. On the other hand, the process and RS can present unexpected results, using the SMAW, FCAW and GTAW processes in ballistic steel butt welds, it was observed that the HAZ when subjected to projectile penetration testing, the SMAW process with higher residual stresses, withstood the test, and the others even with lower stress levels were penetrated [23].

Regarding the application parameters of the techniques, the two most researched are the constraints of the welded structure and the welding sequence. The degree of restriction refers to the resistance of the welded joint to the contraction and thermal expansion free of the heated material [24]. The constraint of the welded joint has a strong influence on the level of residual stresses, so much so that it can be considered that there are the inherent residual stresses produced naturally by the internal misfit and auto equilibrium and the reaction stresses that are a consequence of welded parts usually trapped by mechanical mechanisms. However, the basic principle for good welding practices reveals that longitudinal constraints more efficiently decrease residual welding stresses [25]. Otherwise, the deposition sequence of the welds also has a direct impact on the distribution of RS and distortions in the most varied forms and welded geometries. In studies involving the simulation of butt welds in plates and circumferential welds in pipes, this influence became notorious [26]. Simulating the J bevel deposition sequence in austenitic stainless steel tube-block joints (SUS304), the results indicated that this sequence has not only significant influence on the gradient of RS, but the last pass has a more significant gradient at the end [27].

Finally, no class of factors is further studied than the primary parameters of electric arc welding (U, I and $\nu_s$), the interaction between these parameters generates the energy required for arc opening, producing thermal cycles and temperature peaks that generate thermal stresses and are the driving force of phase transformations during weld pool cooling. From this arc energy only part of it participates effectively in the fusion that generates the weld metal. It is important to mention that heat input has been erroneously referenced in many articles as synonymous with welding energy, which are not equal. However, its quantification is difficult due to numerous experimental difficulties [7, 28]. The basic relationship of the heat input with RS refers to its origin from the conversion of thermal stresses, as already mentioned.

Thus, any change in the primary parameters will change the formation settings of the residual stresses. That is, when the welding speed growth, the heat input decreases and residual stresses increase by producing a strait isotherm [12, 29]. In addition, the increase in welding energy is directly proportional to the magnification in RS present in the welded joint, also causing an enlargement the peak of tensile stresses [9, 24]. Otherwise, welding energy is so important by controlling the transformation temperature of weld pool phases that it is possible to combine the microstructure with acceptable resistance and toughness with low tensile or even compressive residual stresses. These transformations are governed almost entirely by austenitic transformation in the case of ferrous alloys.

## 3. Evaluation and measurement of residual stresses in welded structures

### 3.1 Directions and magnitudes

The evaluation of RS states is often uncertain and the reason for this is related to several specific aspects that should be considered in the measurement of residual stress, since analyses are sometimes problematic and dubious and that residual stress notation is not always used adequately by some authors [30]. Because there is no standardization system that convinces and guides the distribution of residual stresses, each author uses what suits him. However, this point is paramount for proper understanding and knowing the possible effects that can cause on a welded part or structure. Thus, considering that there is no right or wrong way, the criterion used is based on the one most referenced by the specialized academic community, according to the model in **Figure 1**. Generally, the analyses are performed two-dimensionally, considering the longitudinal ($\sigma_y$) and transverse ($\sigma_x$) directions studied, always having as reference the weld bead. The stresses of the normal plane ($\sigma_z$) are less measured, but should not be discarded in any hypothesis, even though the thickness of the plate is conditioned. Finally, it is important mentioning that, in practice, the most significant component is composed of longitudinal stresses, and generally equals, on average, three times the transverse stresses to the weld bead, where welds of a single pass are considered and that there are no temperature gradients on the z axis [25, 31].

Still, within the study of residual stress generated by arc welding two parameters are essential for understanding it: (i) the behavior of this RS (in MPa), that is, if it

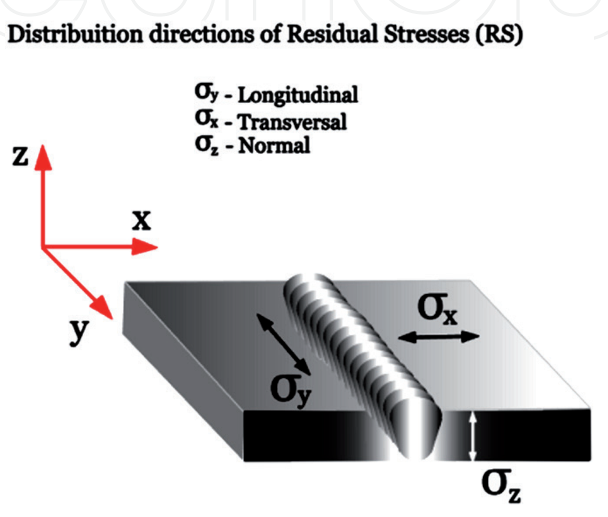


**Figure 1.**
*Schematic representation of the distribution of RS directions on a three-dimensional plate.*

is tensile to positive (+) or compressive values for negative (–) values; (ii) and its effect on the welded component, i.e. defects or failures related to residual stresses. Therefore, it is worth mentioning that the relationship between tensile and compressive residual stresses lies in the fact that the first has a degradative effect on the welded part, while the other can contribute in a beneficial way in many cases [3, 32]. However, this statement is often justified, due to the absence of knowledge of the existing residual stress state and its consequences, which is used to explain unexpected failures most often.

Based on the various works already published, it is possible to have a predictability of RS profiles in any of the directions of the plane, considering the metal alloy and the geometry of the welded joint, with this, represents a pattern of longitudinal residual stresses for certain alloys considering plates with butt welds [11].

When it comes to the effect of residual welding stresses on the behavior of materials, depending on their magnitude these stresses affect not only the welded joint, but also, on some occasions, the entire structure. Generally, tensile stresses are attributed to decreased fatigue life and corrosion resistance (cracks by stress corrosion), in addition to hydrogen embrittlement, etc. It is often suggested that the maximum magnitude of the tensile residual stresses should not approach the yield limit of the material, which would lead this or the welded joint to premature failures, especially near the weld. On the other hand, compressive residual stresses when at high magnitudes are usually attributed to decreased buckling resistance of the base metal, provided that the component is subject to compressive loading. Finally, in this way, it is expected that any welded structure, the simplest, will have residual stresses at any magnitude at controlled levels, or that approach the neutral line, since the peaks, even unprovoked, only increase the risk of unwanted and un predictable failures.

### 3.2 Measurement techniques

There are different measurement techniques to evaluate the residual welding stresses in a welded component. Some are based on the measure of relieved deformation, due to localized removal of material, called destructive techniques. Others are based on the interaction between the residual stress field and the physical properties of the material, called non-destructive (NDT). However, numerous authors also classify some techniques as semi-destructive, since their use does not compromise the physical structure of the material.

#### *3.2.1 Destructive techniques*

Among the various techniques for measuring residual stresses considered destructive, there is the sectioning technique that is based on the measurement of deformation due to the release of residual stress after removal of the material from the sample. The sectioning method consists of making a cut with appropriate instrument in the sample in order to release the residual stresses that are present in the cutting line. For this purpose, the cutting process used must not introduce plasticity or heat into the sample, so that the original residual stress can be measured without the influence of the effects of plasticity on the surface of the cutting planes [33]. In [32, 34], a cut-off sequence used by the technique to measure residual stress is shown schematically in literature.

Another technique belonging to this classification is the contour technique, which is based on solid mechanics, which determines RS through an experiment that involves carefully cutting a sample into two parts, measuring the resulting deformation due to the redistribution of residual stresses. The measured strain data is used to calculate residual stresses through an analysis that involves a finite element model that considers stiffness and geometry as just one parameter in the analysis, providing only one result [32].

There is also the technique of removal of layers, whose principle of action consists in the removal of material that contains residual stress, this removal of material causes unbalance in the workpiece that may result in deformation of the same. Removal of the tensioned material is performed continuously and the measurement of the curvature (deflection) of the sample is also done at the same time of removal, the residual stresses originally present can be deduced. Therefore, this technique provides a quick determination of residual stress as a function of the depth below the surface [35]. According to [34], the variation of deflection (curvature) after the removal of a layer of material, from a thickness e', can be related to the stress $\sigma_e$, which acted on that layer.

Other destructive techniques are the Hole-Drilling Method and the Ring Core Method. The hole-drilling technique is the most used general technique for measuring residual stresses in materials. It uses standardized procedures and has good accuracy and reliability. The test procedure involves some damage to the sample, but this is often tolerable or repairable. For this reason, the technique is sometimes called semi-destructive.

Otherwise, the hole-drilling technique is the most used due to its greater ease of use and to cause less damage to the sample. Finally, there is the Deep Hole Drilling Method, which is considered a variant of the hole-drilling and ring core techniques, with the difference of performing an analysis on thicker materials [33]. According to [36] the basic procedure involves the machining of a reference hole through the sample and the subsequent removal of a column of material, centered on the reference hole, using a trepanning technique. The diameter of the reference hole is accurately measured along its length before the material column is removed. Because, when the material column is removed, the stresses are relaxed, the dimensions of the hole diameter of the reference column are changed. In this context, the dimensions of the column and the reference hole are measured again and the residual stresses are calculated from the dimensional changes caused by the removal of the material from the greatest deformation of the sample in the analyzed area.

### *3.2.2 Non-destructive techniques (NDT)*

Within this classification of techniques, there are the magnetic techniques that are based on the relationship between magnetization and the elastic deformation existing in ferromagnetic materials, as experiments demonstrate that a piece of steel wire, once magnetized, will undergo elongation in the direction of magnetization, while once pulled it will magnetize in the direction of the pull. Two techniques have been extensively explored in the literature, in addition to being applicable in industry: the Barkhausen noise technique and the magneto-striction technique. The first is based on the change in the magnetic microstructure caused by the presence of stresses, while the second is based on measurements of the permeability and magnetic induction of the material [34].

The most common magnetic technique is the Barkhausen noise magnetic technique. Ferromagnetic materials present magnetically ordered microscopic regions, called domains, where each domain is magnetized based on the crystallographic directions preferred to the magnetization. Furthermore, a domain does not coincide with a grain, since within a grain there are several domains, which are separated by walls, in which the direction of magnetization generally changes by 90° or 180°. In [34] also states that when a magnetic field or mechanical stress is applied to a ferromagnetic material, changes occur in the structure of the domains caused by the sudden movement of the walls. These changes cause variations in the average magnetization of the component, as well as in its dimensions. Thus, if a conductive coil is placed close to the sample while the domain wall is moving, the resulting change in magnetization will induce electrical pulses in the coil. When these electrical pulses are produced by the movement of all domains, a signal is generated, called "Barkhausen noise." The extent of movement of the domain walls, that is, the intensity of Barkhausen noise, depends on the stresses present and the material's microstructure. The measurement depth for practical applications of this technique on steel varies between 0.01 and 1 mm. The authors [2] present results of stresses measured by this technique.

Another non-destructive technique is Neutron Diffraction, which, similarly to the X-ray diffraction technique, measures the crystallographic spacing between the crystalline planes. This spacing is affected by RS or applied stress [37]. This technique can measure the elastic deformations induced by residual stresses in the entire volume of the relatively thick steel components with a spatial resolution as small as 1 $mm^3$ [2]. The authors [3, 36] claim that the greatest advantage of neutron diffraction over x-ray diffraction is the great depth of penetration that neutrons can obtain, which makes it capable of measuring a greater depth, reaching 25 mm in aluminum and 25 cm in steel. According to [36], due to the high spatial resolution, neutron diffraction can provide complete three-dimensional deformation maps in an engineering component, that is, for each measurement point, the deformation can be measured in three orthogonal directions along the axis Sample. Practical applications of the technique and the theoretical background can be seen in [34, 38, 39].

There is also the x-ray diffraction technique (XRD). This XRD technique was first proposed by Lester and Aborn in 1925 [34]. However, the technique is restricted, its main restriction being the depth of analysis of the samples, since the beam of x-rays can only penetrate the distance of some atomic planes, about 1–50 μm [36]. For [40], the penetration is around 25 μm and for [41] it ranges from 5 to 20 μm, that is, the XRD makes a subsurface assessment of the stresses. To overcome this restriction, [37] states that for measurements at a greater depth, that is, greater than 0.013 mm, destructive techniques such as the layer removal technique should be used. In the evaluation by XRD, the residual stress is calculated from the measurement of the deformation in the crystal of the polycrystalline aggregate, compared to the network parameters of the crystal of this same material without suffering deformation. When a beam of x-rays is directed towards the surface of a body, a part of these rays is absorbed by the atoms while another part is sent back in all directions of the irradiated area. This technique basically measures the maximum diffracted ray intensity for a given scanning angle. From this angle it is possible to obtain the interplanar spacing of the diffraction planes determined by Bragg's Law [5, 42]. For the measurement of residual stresses using XRD, there are three basic techniques [3, 42]. Techniques, double exposure, single exposure, and multiple exposures or sen2ψ. The amount of exposure refers to the amount of exposure angles, such as angles between the normal at the surface of the part and the plane formed by the incident X-ray beam and the diffracted beam. The sen2ψ technique is one of the most classic [43]. This method is capable of measuring stresses with an accuracy of ±20 MPa, with a penetration depth in the order of microns under the sample surface [2, 4]. This technique and its history of development are described in [5, 43, 44].

Finally, there are the ultrasonic techniques, which are based on the acustoelastic effect, which is the influence of the state of stress on changes in the speed of propagation of the ultrasonic wave as it travels through the material, developed by [45], using the theory of finite strain and third order terms of [46] elastic strain. The techniques that use Critically Refracted Longitudinal Waves (Lcr) and shear waves [32] stand out. The ultrasonic technique that uses Lcr waves, according to [47], is a special case, as these to be generated, must be introduced into the material with an angle of incidence slightly greater than the critically refracted angle (first critical angle), based in Snell's Law. This wave propagates parallel to the surface of the material to be analyzed, as can be seen in the works of [47–49]. In addition to these, numerous studies are available in the literature, such as [41, 50–52].

The other ultrasonic technique is acoustic birefringence (AB), which relates the relative difference between the velocities or the time of two shear ultrasonic waves with polarization directions orthogonal to each other, indicating the degree of anisotropy of the material, where birefringence is determined by (Eq. (4)) [53–59]. In this equation, $V_l$ is the velocity of the shear ultrasonic wave with the polarization direction aligned with that of the lamination, $V_t$ is the velocity of the shear ultrasonic wave with the transverse to lamination polarization direction, $t_l$ is the travel time of the ultrasonic wave with the polarization direction aligned with the material lamination direction and tt the travel time of the ultrasonic wave with the polarization direction perpendicular to the lamination direction.

$$B = \frac{V_l - V_t}{\frac{V_l + V_t}{2}} = \frac{-(t_l - t_t)}{\frac{t_l + t_t}{2}} \tag{4}$$

The acoustic birefringence B depends, therefore, on the initial anisotropy $B_0$ and on the main difference in tension ($\sigma_1$-$\sigma_2$), as well as the anisotropic speed of the wave not being directly linked to the effect of stress due to the presence of this initial anisotropy of the material [60]. When the directions of the principal stresses coincide with the axis of the initial anisotropy, the relationship between the difference of the principal stresses with the birefringence is established according to Eq. (5) [61].

$$B = B_o + k(\sigma_1 - \sigma_2) \tag{5}$$

In this equation, $B_0$ is the birefringence for the material in the stress-free state and k is the acustoelastic constant that relates the stress variations with the birefringence. This technique has been used a lot lately in practical measurements of residual stresses. In Brazil, since the end of the 1990s by [62] in projects with Petrobras. More recently, by [63], where the technique was used to measure residual stresses generated by GMAW and CW-GMAW welds. **Figure 2** shows the assembly of the RS measurement equipment by acoustic birefringence, identical to that used by researchers.

A comparison between non-destructive methods can be seen in **Figure 3**, where x-ray diffraction techniques (the mean between $\sigma_y$ and $\sigma_x$) and acoustic birefringence (the difference between $\sigma_y$ and $\sigma_x$ in MPa), in order to verify the main similarities and differences regarding the values obtained and the magnitudes found. The measurement was made on naval steel plate (ASTM A131 grade AH32) with a thickness of 9.5 mm and dimensions of 1200 mm by 800 mm, considering 3 equidistant lines separated by 300 mm and 100 mm from the edge in the longest direction. Each line has 9 points separated by 120 mm from each other on the same line.

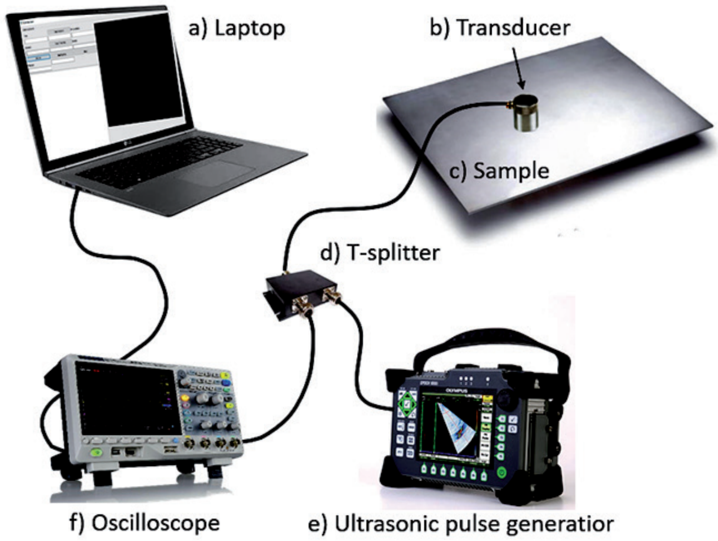


**Figure 2.**
*Ultrasonic system used to measure RS by acoustic birefringence.*

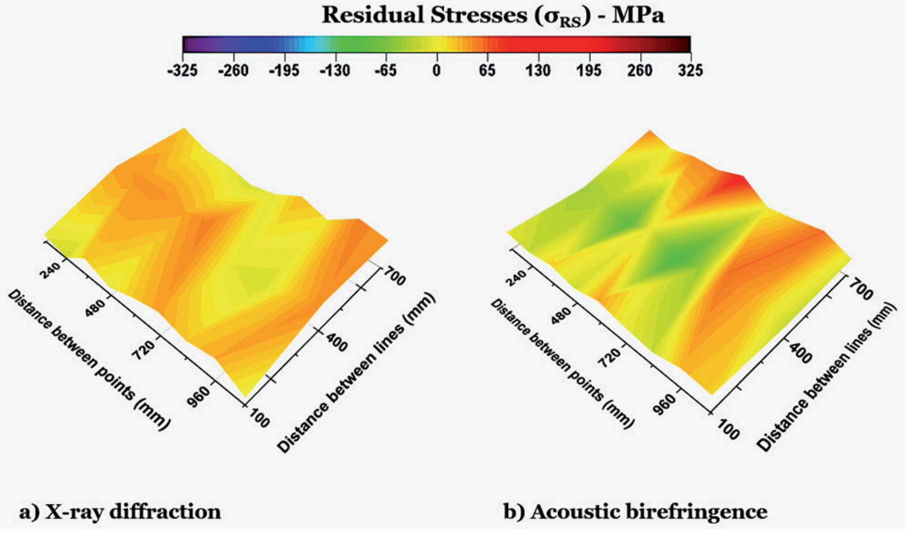


**Figure 3.**
*Comparative measurement in a naval steel sheet (ASTM A131 grade AH32) between the methods: (a) X-ray diffraction (XRD) and (b) acoustic birefringence (AB).*

Through **Figure 3**, there is a reasonable difference between the data obtained, where the plate measured by XRD is predominated by yellow and some peaks in more orange, however the range of residual stresses varied from −17 MPa to 50 MPa, while measuring with AB, it showed the central line with more compressive points, in green and other red peaks indicating tensile stresses, with values ranging from −112 MPa to 103 MPa. However, this disagreement in the results is mainly due to two factors, first, due to the difference in the depths analyzed between the measurement techniques, where the XRD method is more superficial and the AB method analyzes the entire plate thickness. Second, due to the specific methodology of each technique, that is, the XRD shows the punctual and unidirectional RS, while the AB shows the average difference of the main RS, but this result was already predicted. Although both techniques were able to clearly show the presence of RS in the component welded by CW-GMAW.

## 4. Techniques for controlling or reducing residual stresses and distortions

The relief of residual stress in welding has as premise the production of a rearrangement of atoms or molecules from their position of momentary equilibrium, from where the material leaves from a larger state to another of lower tension (lower potential energy), a more stable position. The analysis of residual stress and welding distortion, seen from a historical perspective, developed largely independently of each other, although, from the physical point of view, they are closely related [11].

To design and manufacture a structure with the least number of defects it is essential to have: an appropriate design; an appropriate selection of materials; suitable welding equipment and procedures; good manpower; and strict quality control [1]. The authors [64] showed that the procedures for reducing RS's are directly linked to the reduction of deformations generated during the joining process. There are several examples of methodologies that can be used to perform the relief of RS's, classified into three major categories: Thermal, Mechanical and Chemical, which can be performed before, during and after welding. There are many stress relief techniques that can be classified as conventional, due to their extensive use and the most varied applications in welded components, such as: hammering, heat treatment (pre- and post-heating), shot peening, mechanical tensioning, among others. However, non-conventional alternative techniques will be approached.

### 4.1 Procedures for the adequacy of the quantity of material deposited in the weldment

Since the RS in welding are the result of non-uniform deformations caused by the thermal gradient of the process, which can be attenuated by reducing the volume of weld metal deposited and adapting the chamfer design, which tends to decrease the heat transferred to the part and consequently, it causes a decrease in the RS levels and the degree of distortion of the weldment. The adequacy of the quantity of material must be chosen at the stage of development of the project and welding procedures. **Figure 4a** shows the representation of angular deformations in butt welds with various thicknesses, demonstrating that the angular distortion increases as a thicker plate is used, due to the greater amount of deposited material, resulting in a greater contraction during the solidification process. For small thicknesses, the angular deformation is not significant due to the high homogeneity of the temperature field through the thickness of the sheet. Plates with

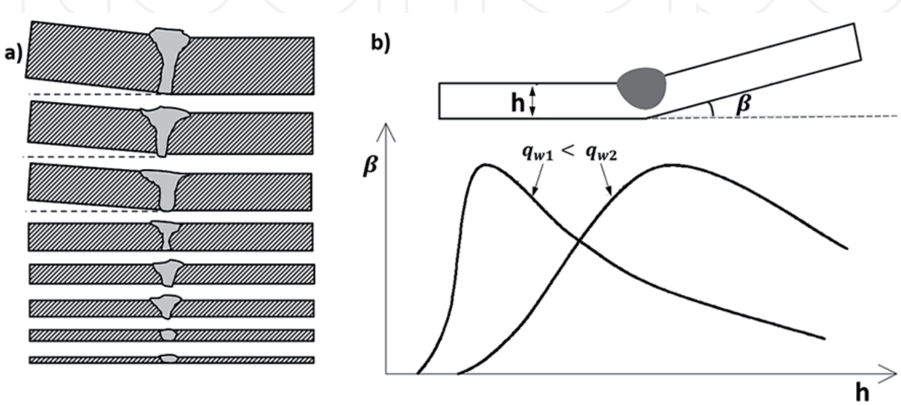


**Figure 4.**
*Representation of angular distortions. (a) plate distortions in butt joints with various thicknesses and (b) angular distortion depending on the thickness of the plate and the heat input $q_w$.*

intermediate thickness correspond to the highest angular distortion value [64–66]. However, for plates with great thickness the value of angular deformation became low, due to its greater rigidity. **Figure 4b** shows, in a qualitative way, the angular deformation as a function of the thickness of the plate and the heat input, $q_w$ [67]. The increase in heat delivered to the plate can be represented using different welding parameters, such as increasing the feed value, in the case of the GMAW process, using the welding torch manipulation, weaving, and reducing the welding speed. The variation of these parameters generates an increase in material deposited per unit of length, consequently greater heat input, which shifts the curve to the right (**Figure 4b**). The authors [68] observed in their study that by applying a variant of the GMAW process to the CW-GMAW process, a reduction in the width of HAZ was obtained. This trend would be consistent with faster cooling rates produced using the CW-GMAW process, which suppresses ferrite nucleation at the grain boundaries. This reduction in the cooling rate resulted in less misalignment of the welded joint in the CW-GMAW process, compared to welding performed by the GMAW process.

### 4.2 Processes of construction and arrangement of the weldment

The authors [64] highlight the need to establish in advance the meanings of the welding sequence and the deposition sequence used in the construction of a structure. The welding sequence is closely linked to the assembly sequence, which must be established during construction planning, observing the manufacturing feasibility in order to minimize residual stresses and distortions. The manufacture of a structure formed by several unions, must follow some basic rules. In summary, the welding process must be performed symmetrically in relation to the neutral axis of the structural set, in order to counterbalance the forces arising from the contraction of the weld beads. However, it is not always possible to follow welding procedures determined in the project, in practice, these procedures will be decided when the construction inconveniences are observed in the field.

The deposition sequence refers to the progression of the formation of the beads during the execution of the welding, being able to use several types of progression that can be combined in different ways. As examples of sequences and progressions one can mention: continuous sequence (continuous pass); symmetric sequence; sequence with guided passes; progression by continuous passes and sequence of backwards passes.

The researchers [69, 70] developed studies on welding sequences, in order to promote the reduction of deformations in stiffened panels. The authors [69] used the robotic FCAW welding process in T joints of ASTM 131 grade AH32 stiffened steel panels. **Figure 5** shows examples of welding sequences used. After welding, they observed that sequence 3 (S3) presented the lowest global distortions value. In addition to the deformation analysis, he quantified the RS values using a portable X-ray diffraction equipment. **Figure 6** presents the 3D representation of the mean RS values in the longitudinal $\sigma_y$ and transversal $\sigma_x$ directions along the X axis. As the RS is closely linked to the behavior of the distortions, the panel that presented the lowest RS values was the sequence S3, with 59 and 86% for longitudinal and transverse compression stresses, respectively.

The influence of direction, welding sequence and reverse pass welding were analyzed by [70] on the distortions levels. The author uses in his work the GMAW process in short circuit mode, in T-joints of low carbon steel stiffened panels, where five welding sequences were used. Six welds of the same length were deposited in each panel to fix the reinforcements, obeying the order and sequence of welding.

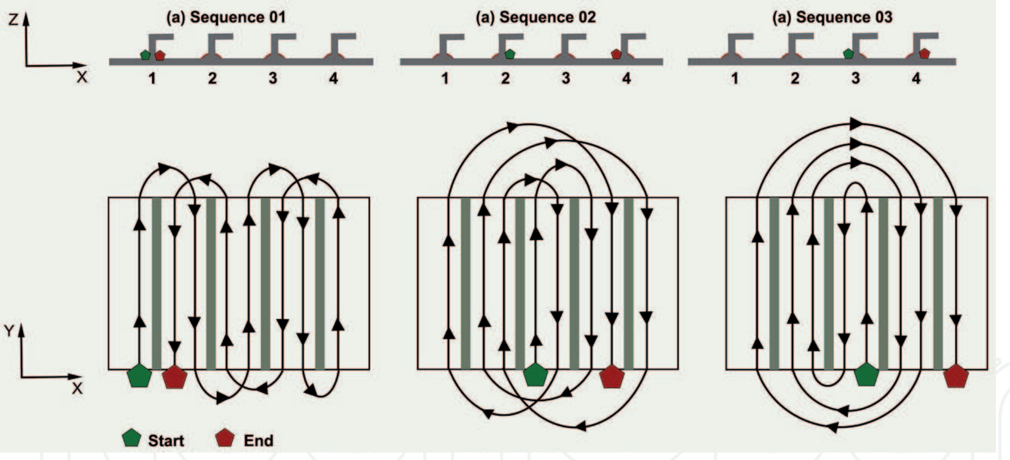


**Figure 5.**
*Examples of welding sequences and directions in the union of hardened panels.*

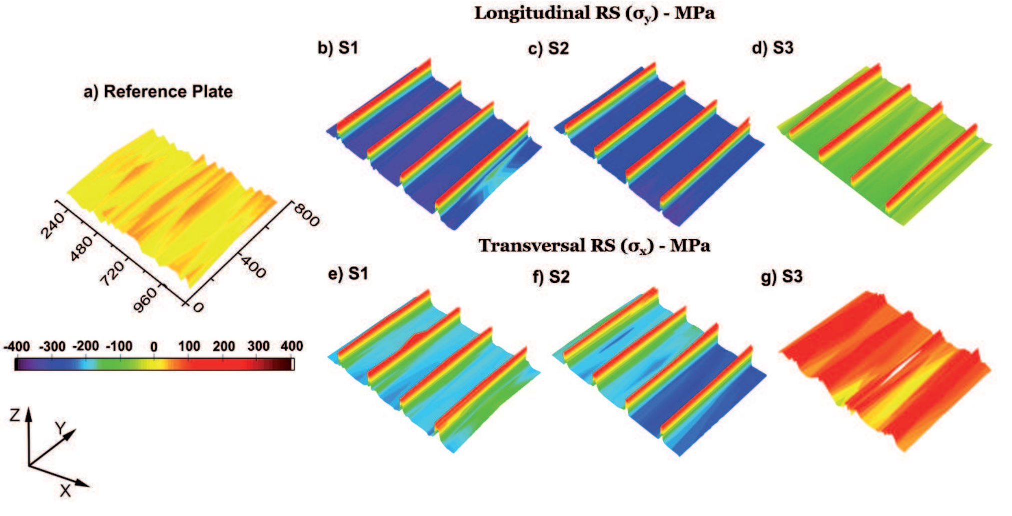


**Figure 6.**
*TR's values in the 3D perspective for (a) reference plate; (b) sequence 1; (c) sequence 2; (d) sequence 3 in the longitudinal direction; (e) sequence 1; (f) sequence 2; and (g) sequence 3 in the transverse direction.*

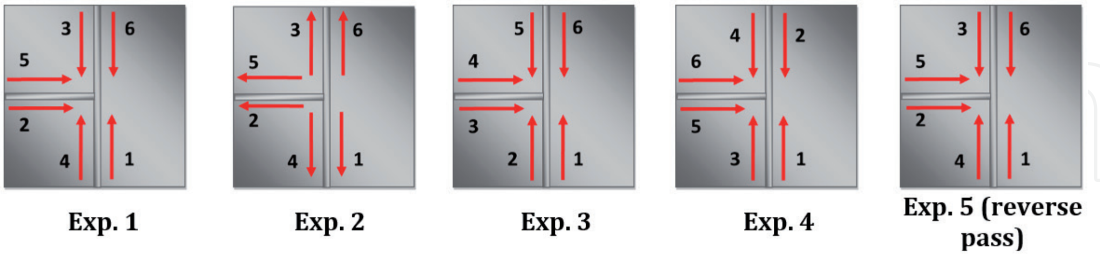


**Figure 7.**
*Schematics of welding sequences and directions for the stiffened panels.*

The welding sequences and directions for fixing the stiffeners can be seen in **Figure 7**. In the fifth sequence, the reverse pass was used, since the weld was divided into three equal segments. The arrow indicates the welding direction.

The taking of the values of distortions of the panels was carried out in the four corners of each panel, adding the values of the distortions to obtain the global distortion of the panel. The average global distortion values measured, **Figure 8**, show that the lowest distortion values are obtained from the pass in the central direction to the ends (Exp. 2) and to the reverse pass (Exp. 5). For Exp. 2, the sequence used

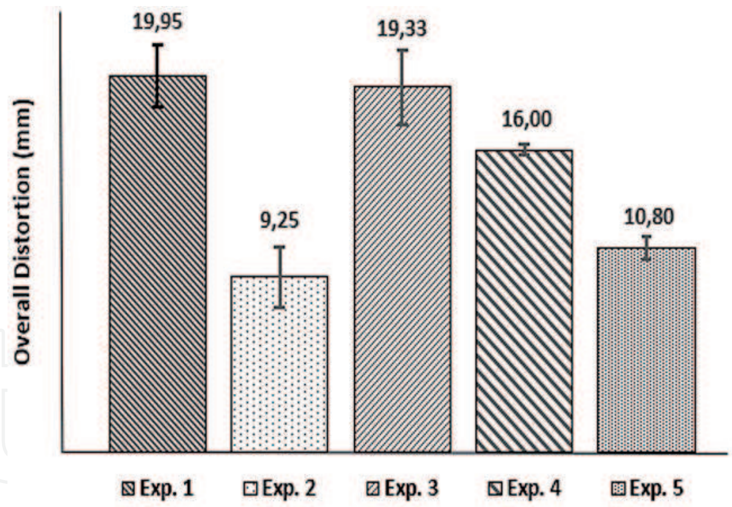


**Figure 8.**
*Overall distortion of the experiments.*

generated values consistent with those found in numerical studies [71–73]. Similarly, the results are corroborated by the work of [69], where it was observed that the welding sequence that provided the lowest distortion value must be performed from a more rigid point (central part) to one of less rigidity (extremities), resulting in less flexion of the panel and consequently lower values of RS. Exp. 5 obtained values very close to Exp. 2, due to the greater control of the temperature differential applied to the welded sheet and to a more uniform distribution of residual stresses [71]. However, this gain in the distortion values must be well considered, since a longer time was used to make the stiffener joint.

### 4.3 Vibratory stress relief (VSR)

The VSR process has achieved great prominence in the relief of RS's induced by thermal processes, such as welding, casting, but not those induced by cold work, being applied in several materials, low and medium carbon steels, stainless steels and aluminum alloys, not having an expected effect on copper alloys. VSR offers several advantages compared to the PWHT (Post Weld Heat Treatment) process: low time and energy spent, low thermal deformation and no change in the mechanical or metallurgical properties of the material [11, 65]. However, there are numerous conditions that must be considered when using the VSR and PWHT processes. Within the conditions employed by the authors, a lower RS value was obtained for the use of both processes.

The basic premise of this method is the relief of the workpiece RS with a region where the natural stress has been changed. When the part is subjected to vibrations below its new frequency, the metal absorbs energy, gradually redistributing the stresses and the resonant frequency returns to the point corresponding to a residual, or almost free, state [20]. The search for greater productivity for the arc welding process has generated efforts by researchers to develop the VSR process, to act during the welding process, that is, Vibration assisted welding (VAW), which can reduce most expenses related to post-weld vibrations or heat treatments [74].

### 4.4 Optimized welding processes

Aiming at reducing the values of deformations and RS's, the market has been promoting the improvement of welding processes, such as, for example, better stability in metal transfer, methods of controlling the waveform of sources, feedback of parameters during the process, reduction of heat input on the material to be welded, among these processes the CW-GMAW (CW)® stands out. It is a process derived from the GMAW process. The CW-GMAW process uses the feeding procedures to those of the GTAW process with automated feeding, it presents itself as an alternative to increase productivity without increasing the heat input in the melting arc/puddle system. The respective process uses the introduction of an additional wire, at room temperature, in the atmosphere of the arc, generated by the main wire, through an independent feeder and an injector connected to the welding torch [70, 75–78]. In detail, **Figure 9** illustrates the entry of the non-energized wire into the arc atmosphere in the CW-GMAW process.

It is possible to highlight several advantages of the CW-GMAW process over conventional processes, among which we have the one presented in the work of [70, 75]. The authors pointed out that the introduction of an additional wire improves the melting rate, tending to decrease the heat input to the workpiece, thus, there is a decrease in the values of distortions and consequently of RS. Distortions levels were compared using the GMAW, Surface Tension Transfer (STT) and CW-GMAW processes [70]. With the global deformation values, **Figure 10**, it was possible to observe that the CW-GMAW process obtained the lowest global distortion value, in comparison with the other investigated processes.

In another study, RS values were compared using two measurement techniques, X-ray diffraction and Acoustic Birefringence (BA), using the GMAW and CW-GMAW processes [63]. The analyzes were performed in simple deposition welds, on ASTM 131 grade AH32 naval steel plates, rigidly attached to a support to ensure a condition close to that found in real welding, simulating the dimensional restriction levels of a welded structure. After the deposition of the welds, the values of AB and XRD were measured at previously established points, in the regions of the base metal, heat-affected zone (HAZ) and weld metal (WM). Through **Figure 11** the measurements obtained by XRD showed that the use of the CW-GMAW process decreases the longitudinal stresses in the region near and in the weld bead, a difference was not observed for the transverse stresses. BA measurements showed that the difference between longitudinal and transverse residual stresses tends to decrease when using the CW-GMAW process, compared to the GMAW. These results suggest that the addition of an extra wire to the conventional process reduces the amount of heat supplied to the welded joint and, consequently, prevents the generation of residual welding stresses.

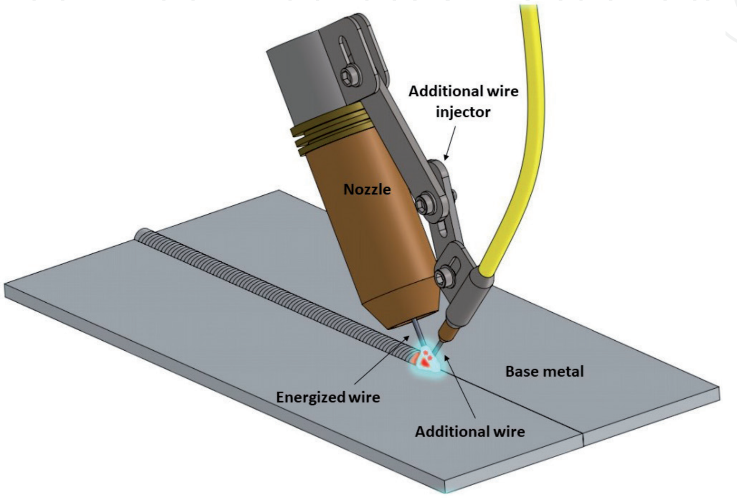


**Figure 9.**
*CW-GMAW process scheme.*

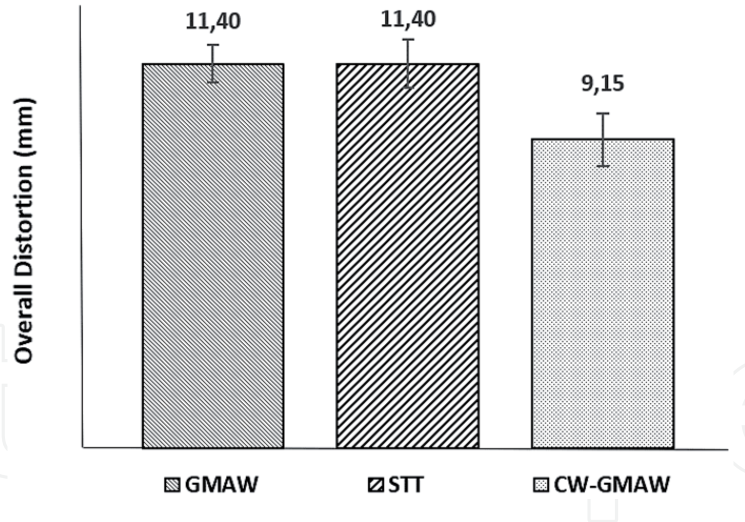


**Figure 10.**
*Overall distortion of the experiments for each process.*

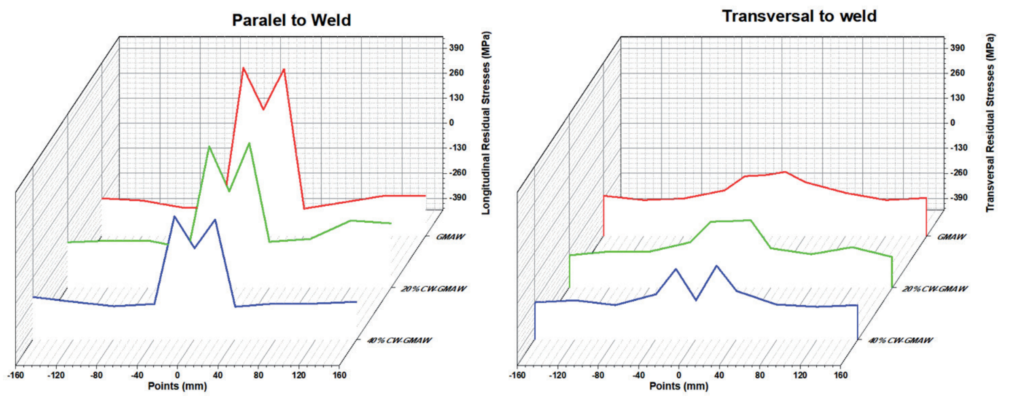


**Figure 11.**
*Comparative between longitudinal and transverse RS with GMAW and CW-GMAW measuring by XRD.*

The authors [68] presented evidence that the use of the CW-GMAW process reduces the residual stress and increases the resistance to fatigue, when compared to samples welded by the conventional GMAW process. The weld bead was made on plates with V joints of ASTM 131 grade A steel. Through a micrographic analysis it was shown that welding by the CW-GMAW process promoted a decrease in the amount of intergranular ferrite and an increase in hardness in the HAZ. SN fatigue resistance curves can be seen in **Figure 12**. Analysis of the results revealed that, for lower levels of reliability, joints manufactured using the GMAW process have a fatigue life at high voltage amplitude levels and greater fatigue life at lower stress amplitudes. However, when a higher level of confidence is considered, weldments made using the CW-GMAW process showed greater resistance to fatigue at both high and low amplitude stress levels.

The versatility and low cost of application of the CW-GMAW process is presented by [76], the authors developed a study on the viability of narrow bevel welding (Narrow Gap Welding-NGW). The tests showed an improvement in stability with the CW-GMAW process instead of the GMAW, and an increase in the melting rate, from 4.9 to 9.7 kg/h, promoting a complete filler weld with just 3 passes (root, filler and finishing), **Figure 13**.

Through high speed filming, in the GMAW process the arc attaches to the side wall, causing erosion and leading to welding discontinuities shown in **Figure 13e**, while for CW-GMAW welding this is not observed, **Figure 13a**. For a better understanding of the metal transfer mechanism [76], welds were deposited on a metal plate with the addition of increasing amounts of extra wire, shown in **Figure 14**.

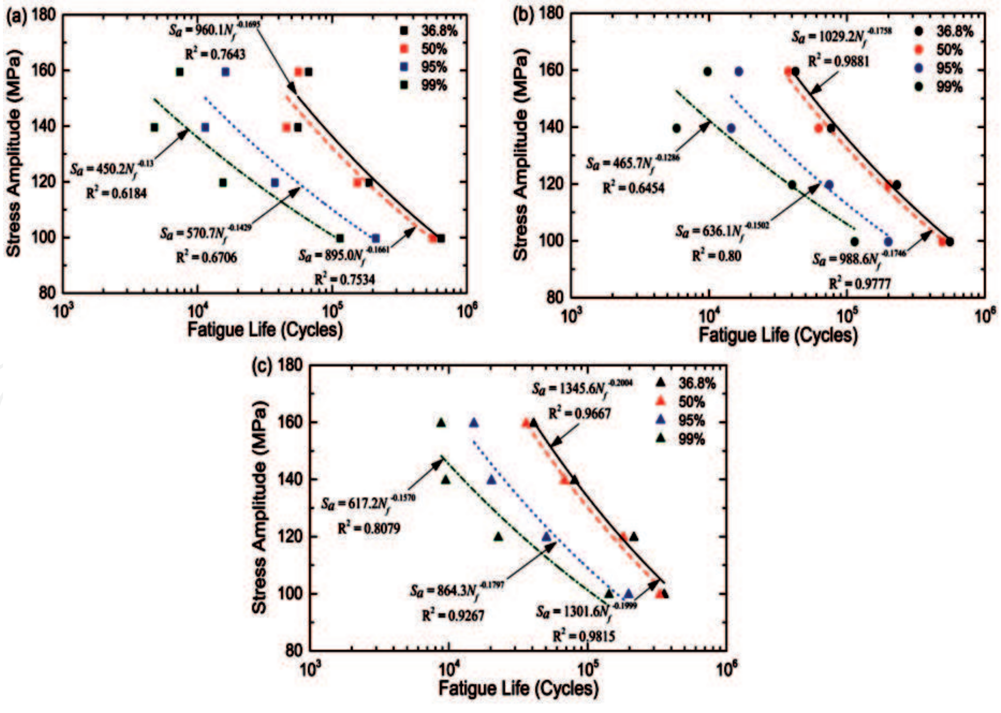

**Figure 12.**
*Fatigue life for different levels of reliability: (a) GMAW, (b) CW-GMAW additional wire of 0.8 mm, and (c) CW-GMAW additional wire of 1.0 mm.*

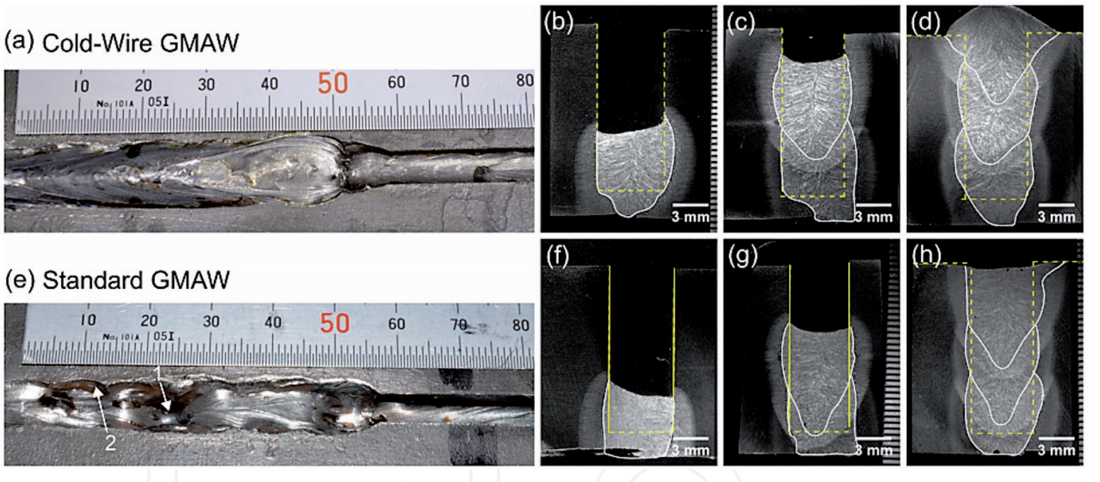

**Figure 13.**
*Appearance and cross section of the bead for welds: (a-d) CW-GMAW; (e-h) GMAW.*

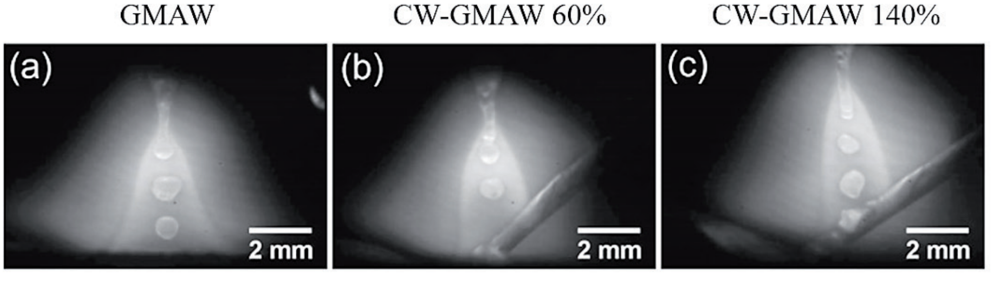

**Figure 14.**
*Influence of the addition of additional wire on the cathode point of the arch: (a) represents the GMAW process, and (b) and (c) represent CW-GMAW welding with the addition of 60 and 140% additional wire, respectively.*

It was found that as the amount of additional wire increases, the position fixing the arc changes from the weld pool to the additional wire, promoting greater stability during the welding process. When larger amounts of additional wire, 140% mass more is inserted into the system, the cathode point moves to the additional wire, which is being feed, shown in **Figure 14c**. This change in the cathode point for the additional wire allows for a more stable welding, thus there is no erosive effect on the wall base metal, the smallest variation in the heat input value for the CW-GMAW points to the stability of the process and its ability to increase the deposition rate without changing the welding heat input.

## 5. Conclusion

It is perceived that identifying, predicting and measuring residual stresses is not an easy labor, the notion of the behavior of residual stresses in a welded component, often implies not only in theoretical terms of their formation and generation, but also to discern which technique best fits to certain types of analysis, although, it is known that all techniques have their advantages and disadvantages. Thus, to help the authors involved in this area to adopt the technique that best suits their research, a broad approach on destructive and non-destructive techniques was explored. Therefore, reaching the conclusion that in addition to the behavior of residual stresses in the welded structure, other parameters must be considered when choosing the technique, for example, the thickness of the joint. Thus, the use of destructive and non-destructive techniques depends not only on having them for use, but also on the need for analysis. In general, non-destructive techniques are more widely used and acoustic birefringence (AB) appears as a promising technique with excellent results compared to more consolidated techniques such as X-ray diffraction. Despite some limitations, the depth of analysis, the ease handling and the low cost of the equipment are very attractive advantages when compared to other methods of the same class or not. Finally, it is clear that, while having knowledge of the mechanisms for generating residual stress by arc welding, its behavior in the weld structure, as well as the techniques used for its measurement, it is certainly more viable to weld without the generation of this voltage, but as this is not possible, a way to control or reduce this voltage is important, and within this perspective there are countless ways to do this, and one result that drew attention within this study was the welding process CW-GMAW, which in addition to reducing the levels of tensile stresses, generates less deformation in the structure. Therefore, in general, a study was successful in its objectives, which was to provide a range of relevant information on arc welding stresses to the community studying the topic.



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## Conflict of interest

The authors declare no conflict of interest.

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