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Residual Stresses Distribution Posterior to Welding and Cutting Processes

Asma Manai

Abstract

Welding is a joining process that leads to considerable change in the local material and the formation of welding residual stresses (RS). Welding residual stresses can be compressive (beneficial for the fatigue life) or tensile (harmful for the fatigue life). In this chapter, a probabilistic analysis of residual stresses distribution posterior to welding processes is carried out. Several researchers stated that the type of the introduced stresses either compressive or tensile depends on several factors. Some of these factors are listed in this chapter. Welding of mega-structures is carried out in the workshops, then a cutting process takes place to construct the exact size of the structural components. This cutting process has a significant effect on the weld residual stresses re-distribution. A study of the re-distribution of the weld residual stress after cutting was performed. It was found that independent of the weld seam length, the residual stresses re-distributed up to 60 % of the weld seam length.

Keywords: weld parameters, tensile residual stresses, compressive residual stresses, as-welded, cutting processes

1. Introduction

Residual stresses have a significant effect on the fatigue life of structures. Surface tensile residual stresses (TRS) can cause harm to structures, components or specimens. However, surface compressive residual stresses (CRS) can improve the fatigue life of the structures, components or specimens. In most cases, welding introduces TRS at the surface. Few cases reported that CRS can be found at the surface of welded structures, components or specimens.

Rossini et al. [1] define residual stresses as the stresses that remain within the Structure in the case of absence of external load or thermal gradients after manufacture and material processing (refer to **Figure 1**). The equilibrium of the self-balanced stress can be translated to equilibrium in x-direction gives Eq.(1).

$$\int_{-h/2}^{h/2} \sigma_{RS,x} dy = 0 \quad (1)$$

Where, h is the plate thickness and $(\sigma_{RS,x})$ is the residual stresses in the x-direction.

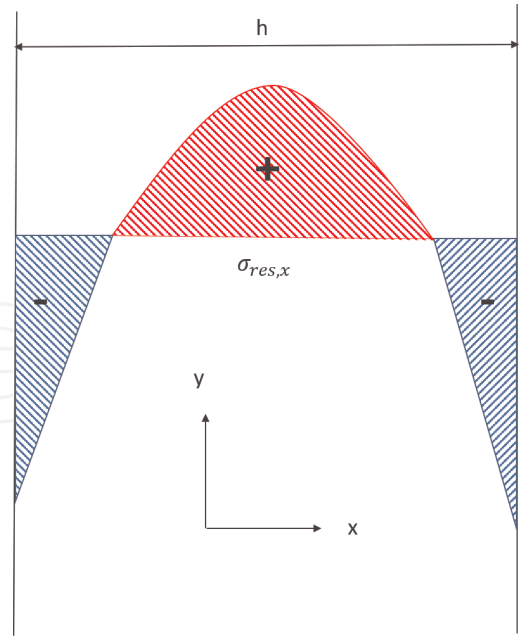


Figure 1.
Schematic presentation of residual stresses distribution.

An external load applied to a structure, component or specimen will lead to a stress distribution. If the structure (component or specimen) has residual stresses and its behavior is still elastic, the material will respond to the sum of the stress distribution of the external load and the residual stresses. Eq.(2) expresses the relation between stress distribution in the material (σ), the externally applied stress (σ_{Ex}) and the residual stresses (σ_{RS}).

$$\sigma = \sigma_{Ex} + \sigma_{RS} \tag{2}$$

In case where the structure, component or specimen is submitted to external cyclic loading (σ_{Ex}), the residual stresses do not affect the stress amplitude ($\sigma_{a,Ex}$), as it is permanently present in the material, therefore, (Eq.(3)). However, it affects the mean stress ($\sigma_{m,Ex}$) (refer to Eq.(4))

$$\sigma_a = \sigma_{a,Ex} \tag{3}$$

$$\sigma_m = \sigma_{m,Ex} + \sigma_{RS} \tag{4}$$

There are several sources that introduce residual stresses, such as production process, heat treatment, welding process, post-weld treatments, etc.

Residual stresses can be classified into two scales namely macro and micro residual stress. RS that occur over long distances within the material are characterized as macro RS. In Withers et al. [2], mentioned that the origins of macro stress are peening, welding, shot-peening and Tungsten Inert Gas (TIG) dressing. While, RS that exists either between grains or inside a grain due to coherence at interfaces, crystalline defects, and dislocation stress fields (Withers et al [2] and Donato et al. [3]) is named as micro residual stresses.

The scale of the residual stress, whether it is micro (intergranular) or macro scale, determines the measurement technique. There is no unique technique that is qualified for measuring all the stress types (micro and macro). Within one specimen or

Technique	Type	Residual stress type
Mechanical	Destructive	Macro-residual stress
X-ray diffraction	Non-destructive (surface method)	Macro and micro residual stress
Neutron diffraction	Non-destructive	Macro and micro residual stress
Ultrasonic	Non-destructive	Macro and micro residual stress
Magnetic	Non-destructive	Macro and micro residual stress

Table 1.
Techniques of measuring residual stresses.

component, measurement of residual stresses using two different techniques, give completely different results. Therefore, for reliable results, it is recommended to select a suitable method for each case. Nasri *et al.* [4], reported that the choice of the measurement technique depends on the scale of the RS.

There are many techniques for residual stresses measurements. These techniques can be grouped into three types namely, nondestructive, semi destructive, and destructive. The following bullets enumerate examples of these techniques:

- Nondestructive: X-ray, neutron and synchrotron diffraction, ultrasonic method, and Barkhausen noise method.
- Semi destructive: Hole-drilling, ring-core, and deep-hole methods.
- Destructive: Sectioning compliance techniques, and contour method.

Table 1 lists the measurements techniques with their corresponding type and residual stress scale that is aimed to measured.

For welding residual stresses, the most used techniques are x-ray diffraction (Monin *et al* [5]) and neutron diffraction (Paddea *et al.* [6]).

In this chapter, Section 2 is meant to determine the mean factors that determine the type of welding residual stresses at the surface and to provide a probabilistic analysis of the shape and type of welding residual stress at the surface. Section 3 gives an overview of the effect of residual stresses on fatigue life and lists the different causes, and reasons for residual stresses relaxation. A re-distribution of welding residual stresses after the cutting process was studied in section 4.

2. Weld residual stresses

The welding process is associated with intensive heating and cooling. This process leads to weld effects at the weld toe and root. Some of these effects are residual stresses, micro-cracks, high-stress concentration, and local change in the material properties. These effects have a significant influence on the fatigue life of the welded structure, component, or specimen. Radaj [7] found that the residual stresses and the geometrical change at the weld toe are the most critical parameters that are determinantal for fatigue. In Manai *et al* [8], Manai [9] and Schijve [10], it was stated that CRS is beneficial for fatigue life, while TRS is harmful and reduces the fatigue life.

2.1 Factors affecting RS distribution

There are many factors that affect the residual stresses distribution in welded structure, component, or specimen. The main factors that determine what residual stresses are present in a welded structure (tensile or compressive at the surface) are listed in the following points:

- The existence of residual stresses in the plates that is resulting from the manufacturing process prior to welding, (before welding takes place).
- The material properties (micro-structures, thermal and mechanical properties) of the weld and base materials.
- The geometry and the shape of the plates being welded.
- The welding procedure (the welding conditions, and the pass sequence in multipass welds).

2.2 Change on the residual stresses distribution

Several factors might modify the residual stresses after welding. These factors can be either during manufacturing process or during the service life of the as-welded structure. Some - but not limited to - of these factors are:

- Surface treatments (peening, TIG dressing, Grinding, etc.), which might cause redistribution of residual stresses due to material removal.
- Cutting process.
- Mechanical loading, such as proof testing or vibration during transportation.
- Thermal treatments.
- Mechanical treatments such as vibrational stress relief.
- In-service repair.
- Crack initiation or loss of the material due to corrosion.

It is highly recommended to consider these factors while assessing the as-welded structure, component, or specimen.

2.3 Type of weld residual stresses

A literature study and a probabilistic analysis of welding residual stresses distribution were performed by Manai et al in [8]. They concluded that the probability of occurrence of TRS at the surface is 0.89, substantially, the probability of occurrence of CRS at the surface equal to 0.11. In addition, Manai et al. [8] developed a method that determines the shape of welding residual stresses distribution through the thickness direction by knowing only the magnitude of surface welding residual stresses. It was assumed that

the residual stresses in the thickness direction at the weld toe has the shape showed in **Figure 2**. Three parameters were used to define this shape which are the magnitude of the surface residual stresses (σ_{RSA}), the maximum magnitude of the subsurface residual stresses (σ_{RSB}), and the depth of the maximum sub-surface residual stresses (D_B).

As welding residual stresses distribution depend on the material properties and the geometry of the plates (thickness of the welded plate), a normalization of the abovementioned parameters that define residual stresses shape is introduced. The magnitude of the residual stresses (σ_{RS}) was normalized by the yield strength (σ_{fy}) of the material, ($\frac{\sigma_{RS}}{\sigma_{fy}}$). The depth of the residual stress (D_B) was normalized by the plate thickness (T), ($\frac{D_B}{T}$). In the section below, a summary of the residual stresses distributions through the thickness direction at the weld toe is stated.

2.3.1 Tensile welding residual stresses at the surface

Based on the probabilistic analysis in Manai et al. [8], in the case where welding introduces TRS at the surface, the following conclusions are extracted (regardless of the material and the thickness of the welded plate):

- A linear regression line connecting the magnitude of the surface RS (σ_{RSA}) and the maximum magnitude of the sub-surface RS (σ_{RSB}) is investigated.
- The mean of the depth of the maximum sub-surface residual stresses (see **Figure 2**), D_B , is 35% of the plate thickness with a standard deviation of 24%.
- The surface magnitude residual stresses (σ_{RSA}) follows a log-normal distribution with a mean value of $-0.35 \sigma_{fy}$ and standard deviation of $0.27 \sigma_{fy}$.
- the maximum sub-surface residual stresses (σ_{RSB}) follows a log-normal distribution with a mean value of $0.2 \sigma_{fy}$ and standard deviation of $0.25 \sigma_{fy}$.

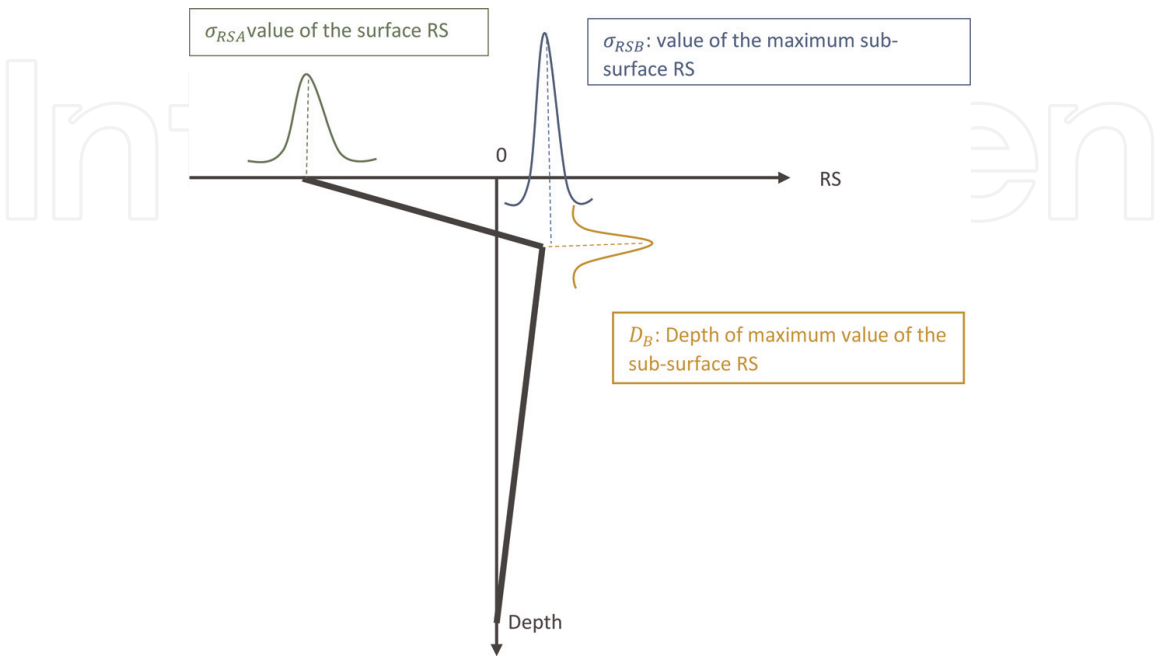


Figure 2.
Schematic presentation of residual shape of RS through the thickness direction.

2.3.2 Compressive welding residual stresses at the surface

In case where welding introduces CRS at the surface and independent of the material and the thickness of the welded plate, the following points were concluded in Manai et al [8]:

- The residual stresses at the surface (σ_{RSA}) have a mean value of $0.57 \sigma_{fy}$ and a standard deviation of $0.12 \sigma_{fy}$.
- The sub-surface residual stresses (σ_{RSB}) have a mean value of $0.59 \sigma_{fy}$ and a standard deviation of $0.39 \sigma_{fy}$.
- The normalized depth of the maximum sub-surface residual stresses ($\frac{D_B}{T}$) follows a normal distribution with a mean value of 10% of the normalized thickness varying with a standard deviation of 7%.

3. Effect of residual stresses on fatigue

Welding residual stresses modify the mean stress experienced by a welded joint under the fatigue loading. In case where high TRS is presented at the welded area, it is assumed that cyclic stresses are fully damaging. Therefore, the effect of welding residual stresses must be taken into account when dealing with welded joints. This effect appears in the calculation of crack growth. As $\frac{da}{dN}$ (a is the crack depth and N is the number of cycles) and ΔK_{th} (stress intensity factors range threshold) depend through the stress ratio ($R = \frac{\sigma_{min}}{\sigma_{max}}$, where σ_{min} is the minimum stress and σ_{max} is the maximum stress) on the mean stress (σ_m). TRS increases the mean stress, therefore accelerates crack propagation. Ultimately, CRS decreases the mean stress, therefore, leads to the retardation of crack propagation.

In the case where TRS is introduced at the welded area, crack propagation occurs even when the structure, component, or specimen is subjected to external compressive stress cycles.

In Manai [9], simulations of the fatigue life of as-welded structures in the case of the presence of TRS at the surface and in the case of the presence of CRS at the surface were carried out. It was stated that the fatigue life increases with a factor of 4.5 times in the case of CRS occurred at the surface after the welding process in comparison to the case where TRS occurred at the surface (after welding).

4. Weld residual stress relaxation after cutting processes

In order to install mega-welded structures such as bridges, off-shores and so on, welding is carried out in the workshop and cutting processes are usually applied. This cutting process is determined depending on the exigences for edge detail and the application Barzoum et al. [11] and Cicero et al. [12]. The most techniques used for cutting are machine cutting and thermal cutting processes. Moreover, there are additional cutting techniques that has recently recognized such as plasma, laser and waterjet. For welded structures, component or specimen a cutting process will introduce relaxation of residual stresses. A few studies emphasized the re-distribution of

the welding residual stresses caused by the cutting process [13, 14, 15]. An analysis of data presented in Liang *et al.* [15] was performed. The used material is Q355B with yield strength $\sigma_{fy} = 359$ MPa. The RS was measured using sectioning relaxation strain gauges.

In order to measure the RS in different weld seam lengths, step-by-step sectioning with measurement of the relaxation stress was performed. Residual stresses in specimens with widths vary between 30 mm and 160 mm were measured. In order to better analyze the data, the magnitude of the residual stresses is normalized with the yield strength of the material (σ_{fy}), and the length was normalized by the plate width (w). The following conclusions were extracted:

For longitudinal residual stresses:

- Regardless of the weld seam length, typical distributions of longitudinal welding residual stresses were found after cutting, (See **Figure 3**).
- After cutting, high tensile residual stresses were measured at the middle of the plate width and low tensile at both edges of the specimen.
- The maximal tensile residual stresses (measured at the middle of the welded plated), gradually decrease with the decrease of the width of the cutted specimen.

For transversal residual stresses:

- Regardless of the weld seam length, typical distributions of transversal welding residual stresses were found after cutting.
- After cutting process, low tensile residual stresses were measured at the middle of the weld seam length and a high compressive residual stresses were measured at both specimen edges.
- After the cutting process, 30% of the width of the welded plate contains tensile residual stresses and 60% contains compressive residual stresses (See **Figure 4**).

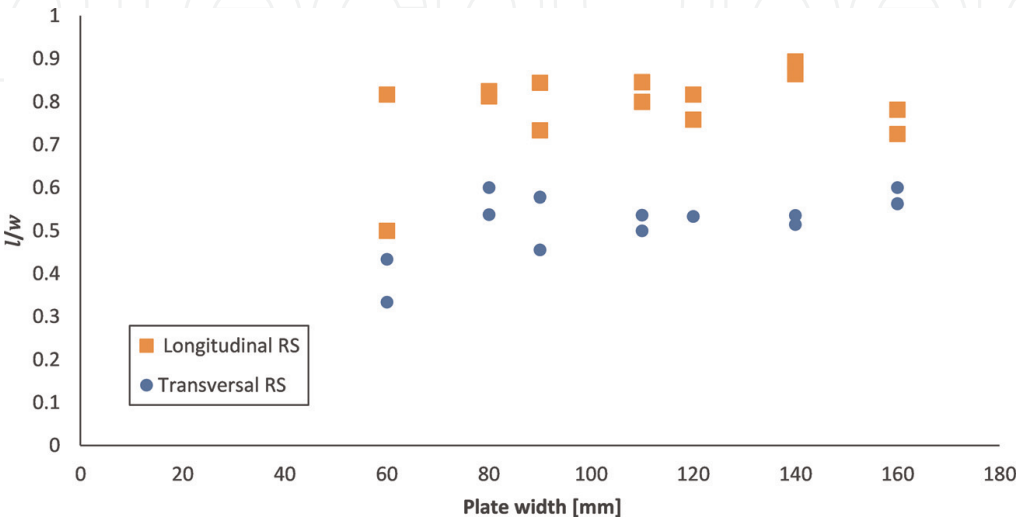


Figure 3.
Plate width as a function of the normalized measured length of CRS after cutting.

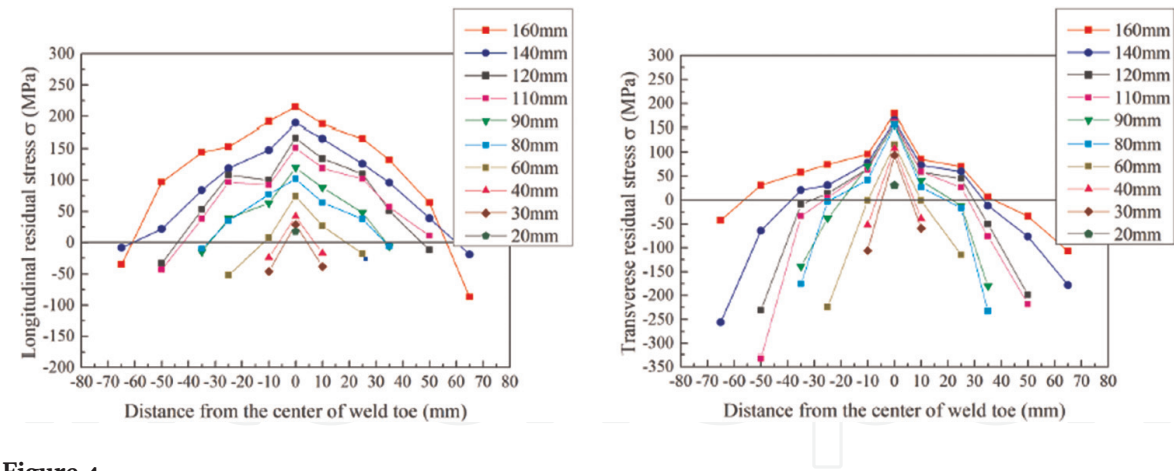


Figure 4.
Measured RS along the weld seam length after cutting, Liang et al. [15].

- Similar to the longitudinal RS, the magnitude of transversal RS decreases gradually with the decrease of the weld seam length (after cutting took place), (See **Figure 3**). In **Figure 3**, l is the length where CRS was measured.

Nomenclature

a	crack depth
D_B	depth of the maximum sub-surface residual stresses
h	plate thickness
l	the length where CRS was measured
N	number of cycles
R	stress ratio
σ_{RSA}	surface residual stresses
σ_{RSB}	maximum sub-surface residual stresses
T	plate thickness
w	plate width
σ_a	stress amplitude
$\sigma_{a,Ex}$	amplitude of the external load
σ_{Ex}	external stress
σ_{fy}	yield strength of the material
σ_m	mean stress
$\sigma_{m,Ex}$	mean of the external load
σ_{max}	maximum stress
σ_{min}	minimum stress
σ_{RS}	residual stresses
$\sigma_{RS,x}$	residual stresses in the x -direction
ΔK_{th}	stress intensity factors range threshold

Abbreviations

RS	residual stresses
TIG dressing	Tungsten Inert Gas dressing
TRS	tensile residual stresses
CRS	compressive residual stresses

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