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STRUCTURAL INTEGRITY ASSESSMENT PROCEDURES FOR EUROPEAN INDUSTRY SINTAP

TASK 4**COMPENDIUM OF RESIDUAL STRESS PROFILES**

FINAL REPORT

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1 – PRESENTATION

1-1 Introduction

Residual stresses can have a detrimental effect on the integrity of a structure and are therefore an important component of any integrity assessment of a welded structure. They are introduced by various manufacturing processes; however, those due to welding are the most common and relevant to this programme of work. Dangerous under predictions of fracture risk can occur, if they are not correctly accounted for, whilst over conservative estimates lead to overestimation of fracture risk. Underprediction is of concern to structural integrity whilst overestimation may have severe financial implications in an industrial situation. Guidance exists for the treatment of known stress distributions; however, it is not available for deriving stress distributions and assessing the range over which they operate. The understanding and treatment of residual stress in integrity assessments is therefore central to the issue of accurate assessment.

1-2 Objectives

Profiles for residual stresses are currently available in various references; however, many of them are not easily accessible and for the most pessimistic assumptions, the value of residual stress is taken as being a membrane stress equal to the material yield stress. Therefore the aim of this document is to propose a single reference source for residual stress profiles taken from the open literature and additional work made in the SINTAP project. This includes the weld repaired, post-welded heat treated and as-welded states. In most of the géometries the effects of differing welding procedures and heat treatments were considered. The profiles presented in this compendium are more realistic than those proposed in the recent codes (except BS 7910.1997 [1]) but still conservative.

2 - SYMBOLS AND ABBREVIATIONS

Symbols	Definition	Units
σ_y	Yield strength	MPa
σ_y^*	Lower of (σ_{yp} , σ_{yw})	MPa
σ_y^+	Greater of (σ_{yp} , σ_{yw})	MPa
σ_{yp}	Yield or 0.2% proof strength of parent metal	MPa
σ_{yw}	Yield or 0.2% proof strength of weld metal	MPa
σ_R^L	Longitudinal residual stress	MPa
σ_R^T	Transverse residual stress	MPa
$\sigma_R^{T,0}$	Transverse residual stress at enter surface	MPa
$\sigma_R^{T,B}$	Transverse residual stress at bore surface	MPa
t	Plate thickness	mm
R	Mean radius of pipe	mm
T	Plate thickness for T weld joint	mm
w	Width of the weld bead	mm
r_0	Dimensions of the yield zone for a thin plate	mm
y_0	Dimensions of the yield zone for a thick plate	mm

3 - CLASSIFICATION AND DEFINITION OF STRESSES

The classification into primary (σ^p) and secondary (σ^s) stresses as defined in BS 7910.1997 [1] will be used for this work.

Primary stresses are those which contribute to collapse, such as applied loads or pressures, and also displacement controlled stresses, such as those associated with thermal expansion.

Secondary stresses are those that are self equilibrating across a weld, producing a zero net force or bending moment. The literature surveys undertaken for this review indicate that residual stress distributions are made up of two components. The first is directly attributable to the welding process, arising from thermal contractions and phase changes that occur in the weldment. The other component arises from mismatch and restraint within the structure itself. This second component varies from case to case.

The data obtained for each geometry are fitted to upper bound tensile profiles, which in general do not self-equilibrate across the weld section. It is therefore recommended that the literature should be consulted for assessments of borderline results in order to obtain the best residual stress profile for the specific joint and material under assessment.

These residual stress profiles are given in the transverse (stresses normal σ_R^T to the weld run) and also the longitudinal (stresses parallel σ_R^L to the weld run) directions. The variation of stress in both through thickness distance and normal distance from the weld centre-line are shown, although those in the through thickness direction are considered to be negligible.

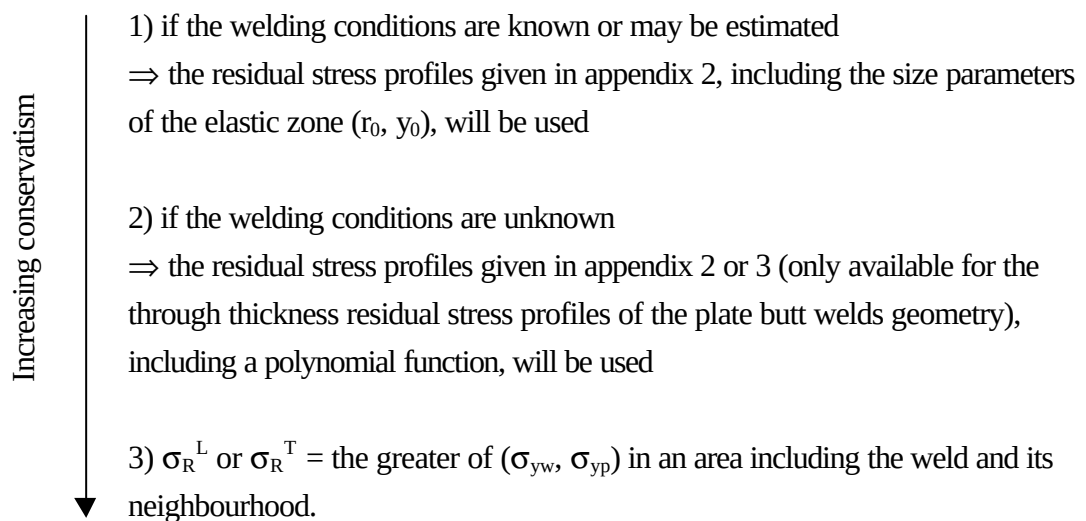
4 –METHODOLOGY

The stress decrease in the stress profiles presented in appendix 2 is expressed in two different ways, depending on the data available in the literature :

- either as a function of the welding conditions and of the mechanical properties of the materials
- or according to a polynomial function from experimental measurements.

The first method was preferred because it is less conservative than the second one.

Consequently, the following rule is proposed for determining the residual stress profiles for a welded assembly :



The calculation of the size parameters of the elastic zone (r_0, y_0) is shown in appendix 1.

5 REVIEW OF RESIDUAL STRESS PROFILES

The residual stress profiles are presented in appendices 2 and 3 for the following geometries :

- plate butt welds	Figure 1	Appendix 2
- plate T butt welds	Figure 2	Appendix 2 and 3
- pipe butt welds	Figure 3	Appendix 2
- pipe axial seam welds	Figure 1	Appendix 2
- pipe T butt welds	Figure 4	Appendix 2
- set in nozzle	Figure 5	Appendix 2
- set on nozzle	Figure 6	Appendix 2
- repair welds	Figure 7	Appendix 2

This data obtained from the literature review are valid for the following ranges described in table 1

GEOMETRY	THICKNESS (mm)	PROOF STRESS (N/mm ²)	ELECTRICAL ENERGY PER UNIT LENGTH (kJ/mm)
Plate butt welds	24 – 300	310 – 740	1.6 – 4.9
Pipe circumferential butt welds	9 – 84	225 – 780	0.35 – 1.9
Pipe axial seam welds	50 – 85	345 – 780	Not known
T butt welds	25 – 100	375 – 420	1.4
Tubular and pipe to plate joints	22 – 50	360 – 490	0.6 – 2.0
Repair welds	75 – 152	500 – 590	1.2 – 1.6

Table 1 : Validity ranges for as-welded residual stress distributions

For each geometry considered, Figure (a) to (d) represent the variation of residual stresses as follows :

- a - Variation of longitudinal residual stresses at the surface,
- b - Variation of longitudinal residual stresses through the thickness,
- c - Variation of transverse residual stresses at the surface,
- d - Variation of transverse residual stresses through the thickness.

The stress profiles are normalised to the yield stress σ_y (σ_y = yield or 0.2 % proof stress) of the weld metal or parent metal.

The parameter, σ_y , refers mainly to the yield stress of the weld σ_{yw} for longitudinal residual stresses except for few cases. For transverse residual stresses, σ_y , is the lower of the weld metal σ_{yw} and the parent metal yield stress σ_{yp} except when there is a defect of the type listed below.

- 1 - Defects in repair welds,
- 2 - Defects at weld intersections,
- 3 - Shallow defects

Here, σ_y refers to the greater yield stress of the parent metal or weld metal.

For austenitic steels, the high work hardening after the beginning of the plastic deformation, results in a large variability of the material properties. In this case, the yield stress σ_y is defined as the 1% proof stress. To a first approximation $\sigma_y (\epsilon = 1\%) \approx 1.5 \sigma_y (\epsilon = 0.2\%)$

If the defect is being assessed in an area of constant and uniform temperature, the appropriate value of σ_y is the yield stress at the temperature of assessment. If the temperature varies within the defective area, then the appropriate value of σ_y is the maximum value of yield stress which usually corresponds to that at the minimum temperature recorded.

5-1 Plate Butt Welds and pipe axial seam welds

This geometry is the most studied in the literature. The stress profiles shown in Figures 1(a) to (d) are taken from [2], [4] and [12] which refers to a large numbers of welds.

5-1-1 Longitudinal Residual Stresses

The surface profile shown in Figure 1(a) is given for different types of materials (Ferritic steel, Austenitic steel and Aluminium) and for single sided and double sided weld. The influence of the plate thickness is taken into account. The calculation of the residual stress decay (r_0 and y_0 parameters) is given for welding conditions and material properties (see appendix 1). If the weld is asymmetric, side one is the side with the widest weld face (i.e. $b_1 \geq b_2$).

The longitudinal through thickness residual stress profiles are given in Figure 1(b) for both ferritic [13] and austenitic steels.

The relevant equations are :

FERRITIC STEELS :

$$s_R^L / s_y^w (z/t) = 1$$

AUSTENITIC STEEL :

$$s_R^L / s_y^w (z/t) = 0.95 + 1.505 (z/t) - 8.287 (z/t)^2 + 10.571 (z/t)^3 - 4.08 (z/t)^4$$

5-1-2 Transverse Residual Stresses

The surface transverse residual stress profile are given in Figure 1 (c) for the weld components made in ferritic austenitic steel and aluminium. The influence of natural restrained conditions is taken into account.

The profile corresponding to unrestrained plates must be selected for the pipe axial seam welds geometry.

The transverse through thickness profile, available for both ferritic and austenitic steels, is given in Figure 1(d).

The relevant equation is :

$$s_R^T / s_y^* (z/t) = 1.0 - 0.917 (z/t) - 14.533 (z/t)^2 + 83115 (z/t)^3 - 215.45 (z/t)^4 + 244.16 (z/t)^5 - 96.36 (z/t)^6$$

5-2 Plate T-Butt Welds

Little information is available on the subject of residual stresses in the base plate of T-butt welds. The residual stress profiles for plate T-butt welds came from the work reference [1], [2] and [4] but the profiles were modified according to the numerical work of Clergé (1995) where the simulation work is in good agreement with the experimental results.

5-2-1 Longitudinal Residual Stresses

Figure 2(a) shows the surface profile for longitudinal residual stresses are given for different types of materials (Ferritic steel, Austenitic steel and Aluminium) and for two different weld preparation which are T butt weld, T fillet weld in flat plates and in tubular T-joints geometries. The influence of the plates thickness is taken into account. If the weld is asymmetric, side one is the side with the widest weld face (i.e. $b_1 \geq b_2$). The influence

of the calculation of the residual stress decay (r_0 and y_0 parameters) is given for welding conditions and material properties (see appendix 1).

The through thickness longitudinal residual stress profiles are shown in Figure 2(b) for the same conditions but this distribution only applies for defects initiating at or near the toe of the weld.

The profile given in appendix 3 must be considered if welding conditions can't be calculated or estimated.

In this case, for the through thickness profiles and for ferritic steels, there is a decrease in the stress with a maximum compression at $-\sigma_{yw}/3$ for $z = t/3$. The stress then reaches a value of $\sigma_{yw}/3$ at the end of the base plate.

5-2-2 Transverse Residual Stresses

The transverse residual stress distribution of T-butt welds takes into account the width of both weld runs. This simplified surface profile presented in Figure 2(c) is in good agreement with the work of Clergé (1995).

Figure 2 (d) is given for the same conditions than figure 2 (b).

The profile given in appendix 3 must be considered if welding conditions can't be calculated or estimated in this case.

The figure presented in appendix 3 shows the through wall distribution recommended in [3]. The residual stress decreases linearly from tensile yield to $-\sigma_{yw}/3$ at a distance $t/2$ into the base plate, then increases to zero at the extremity.

5-3 Pipe Butt Welds

The residual stress profiles presented are largely consistent with those presented in the references [2], [4], [11] and [12] and were modified by [6] for the high heat inputs.

5-3-1 Longitudinal Residual Stresses

The longitudinal surface profile for both ferritic, austenitic steels and aluminium is given in Figure 3(a) for single sided and double-sided weld. The influence of the plate thickness is taken into account. The calculation of the residual stress decay (r_0 and y_0 parameters) is given for welding conditions and material properties (see appendix 1). If the weld is asymmetric, side one is the side with the widest weld face (i.e. $b_1 \geq b_2$).

The through thickness longitudinal residual stress distribution (figure 3 (b)) for both ferritic and austenitic pipe butt weldments is given as a linear profile defined by $\sigma_R^{L,O}$ at the outer surface and $\sigma_R^{L,B}$ at the bore, where $\sigma_R^{L,B}$ is defined as follow :

$$\sigma_R^{L,B} = A_b \sigma_{y,w}$$

where :	$A_b = 1$	$0 < t \leq 15 \text{ mm}$
	$A_b = 1 - 0,0143(t-15)$	$15 \text{ mm} < t \leq 85 \text{ mm}$
	$A_b = 0$	$t > 85 \text{ mm}$

For a pipe thickness of less than 15 mm, a through thickness tensile yield stress is obtained. The tensile stress at the bore decreases with increasing pipe thickness to a value of zero for a pipe thickness of approximately 85 mm, and then goes to zero.

5-3-2 Transverse Residual Stresses

There is no profile proposed for the surface transverse residual stress profiles presented on Figure 3(c) because there is no sufficient data available in the literature and a geometry sensitive.

In this case the uniform σ_R^T has to be consider equal to the lower of the yield strength of parent metal or weld metal.

The though thickness residual stress profiles are given for both austenitic steels and ferritic steels (fig.3d) as following.

For austenitic steels the through thickness residual profile depends on the thickness.

For a pipe thickness $\leq 25 \text{ mm}$ a linear through thickness profile is given by [11].

The equations are :

$$t \leq 7 \text{ mm} \quad \sigma_R^T = 1.219 \sigma_y^* \left[\frac{2z}{t} - 1 \right]$$

$$7 \text{ mm} < t \leq 25 \text{ mm} \quad \sigma_R^T = (1.5884 - 0.05284 t) \sigma_y^* \left[\frac{2z}{t} - 1 \right]$$

For pipe thickness greater than 25 mm, the profile of residual stresses is defined by the following polynomial expression given by [12] :

$$s_R^T = s_R^{T,B} \left(0.27 - 0.91(z/t) - 4.93(z/t)^2 + 8.60(z/t)^3 - 2.03(z/t)^4 \right)$$

Where $s_R^{T,B}(R/t) = 0.118(R/t)$ for $R/t < 8.5$

And $s_R^{T,B}(R/t) = 1.0$ for $R/t > 8.5$

For ferritic steels, the profile depends on the heat input of the weld and the pipe thickness [12].

For high heat inputs $[(q/v)/t > 60 \text{ J/mm}^2]$, the following through wall cosine distribution is employed:

$$s_R^T = s_R^{T,O} \cos(p z/t) \text{ where } s_R^{T,O} = -1, 0 \quad z \text{ is measured from outer surface}$$

For low heat inputs $[q/v/t < 60 \text{ J/mm}^2]$ the following polynomial stress distribution is retained as defined in Figure 3(d).

$$s_R^T = s_R^{T,O} \left(1.0 - 3.29(z/t) - 26.09(z/t)^2 + 73.16(z/t)^3 - 45.72(z/t)^4 \right)$$

Where $s_R^{T,O} / s_y^* = -0.5 - 0.0083 (q/v)/t$

5-4 Pipe T-Butt Welds

The term Pipe T-butt welds includes pipe on plate welds, and pipe on pipe welds (tubular T and Y nodes). The profiles presented originated from references [2], [7], [8] and [12]. The surface profiles are the same as those recommended for plate T-butt welds. The profiles for pipe on pipe geometry are for the stresses in the chord and not the brace member (figure 4 (b) to 4(d)).

The data used to generate the pipe T-butt weld profiles 4(b) to (d) were obtained from geometry where the ratio of the chord thickness to the brace thickness varied from 1.375 to 2. The ratio t/T varied from 1.375 to 2. Where $t/T < 1.375$, a uniform tensile residual stress of yield magnitude should be

assumed. For cases where $t/T > 2$, the profiles for plate T-butt welds are recommended. The R/r ratios for the pipe on pipe geometry varied from 1.5 to approximately 2.

The profiles given here should be used with caution outside this range. If the radii differ by a large amount (say a factor of 5) then the profiles presented for plate T-butt welds should be considered as a good alternative.

5-4-1 Longitudinal Residual Stresses

The surface profiles are shown in Figure 4(a). They are given for ferritic, austenitic steels and aluminium. The influence of the plate thickness is taken into account. The calculation of the residual stress decay (r_0 and y_0 parameters) is given for welding conditions and material properties (see appendix 1). The through thickness variation of longitudinal residual stresses away from the weld centre line is given in Figure 4(b). These data are obtained from ferritic steels in pipe on plate and tubular T and Y node geometry. Caution should be used in applying this distribution to austenitic steel welds. The relevant equation for ferritic steels is :

$$s_R / s_{yw} (z/t) = 1.025 + 3.478 (z/t) - 27.861 (z/t)^2 + 45.788 (z/t)^3 - 21.8 (z/t)^4$$

5-4-2 Transverse Residual Stresses

The surface profile shown in Figure 4(c) is the same as that presented in Figure 2(c).

The through thickness variation of transverse residuals stresses away from the weld toe is shown in Figure 4(d). These data are obtained from ferritic steels in pipe on plate and tubular T and Y node geometries. Caution should be used in applying this distribution to austenitic steel welds since no data from austenitic steels were obtained.

The relevant equation for ferritic steels is.

$$s_R^L / s_y^* (z/t) = 0.97 + 2.327 (z/t) - 24.125 (z/t)^2 + 42.485 (z/t)^3 - 21.087 (z/t)^4$$

5-5 Set in Nozzle

The surface residual stress profiles (figure 5a) come from the work reference [2]. All the profiles are given for different type of material (ferritic steels, austenitic steels and aluminium). with a residual stress delay calculated according to the welding conditions and materials properties (see appendix 1). The distribution stresses on line AiAo in set-in nozzles is based on the general observation that longitudinal stresses in butt welds can be of weld yield magnitude throughout the thickness. This agrees with [10] (recommendations for cylinder-to-dome welds). The distributions for longitudinal and transverse stresses on line BiBo in set-in nozzles is the same as the distribution at plate T-butt welds and hence it comes from BS7910-1997 [1]. This distribution only applies for defects initiating at or near the toe of the weld.

5.5.1 Longitudinal residual stresses

The surface profiles are shown in figure 5 (a). The influence of the plate thickness is taken into account.

The through thickness profiles are given in figure 5 (b) for two different paths on the weld component (Ai A0, Bi B0). One of these presents a residual stress value equal to the yield strength of the weld metal.

5.5.2 Transverse residual stresses

There is no profile proposed for the surface transverse residual stresses profiles, figure 5 (c) because there is no sufficient data available in the literature and an geometry sensitive. In this case the uniform σ_R^T has to be consider equal to the lower of the yield strength of parent metal or weld metal.

The through thickness profiles presented in figure 5 (d) are also given for two different paths (Ai A0, Bi B0). The distribution of transverse stresses on Ai A0 in set-in nozzles is taken from Sanderson's recommendations for nozzle-cylinder weld [10].

The trough thickness profiles presented in figure 5 (d) are also given for two different paths (Ai A0, Bi B0). The distribution of transverse stresses on Ai A0 in set-in nozzles is taken from Sanderson's recommendations for nozzle-cylinder weld [10].

5-6 Set on nozzle

The surface residual stress profiles (figure 6a) come from the work reference [2]. All the profiles are given for different type of material (ferritic steel, austenitic steel and aluminium). with a residual stress delay calculated according to the welding conditions and materials properties (see appendix 1). The distribution stresses on line AiAo in set-on nozzles is taken from Sanderson's recommendation [10] for cylinder to dome welds. It is based on the general observation that longitudinal stresses in butt welds can be of weld yield magnitude throughout the thickness. This agrees with [10] (recommendations for cylinder-to-dome welds). The distributions for longitudinal and transverse stresses on line BiBo set-on nozzles is the same as the distribution at plate T-butt welds and hence it comes from BS7910-1997 [1]. This distribution only applies for defects initiating at or near the toe of the weld.

5.6.1 Longitudinal residual stresses

The surface profile shown in figure 6 (a). The influence of the plate thickness is taken into account.

The through thickness profiles are given in figure 6 (b) for two different paths on the weld component (Ai A0, Bi B0). One of these presents a residual stress value equal to the yield strength of the weld metal.

5-6-2 Transverse residual stresses

There is no recommendation for the surface transverse residual stresses profiles, figure 6 (c) because there is no sufficient data available in the literature and a geometry sensitive. In this case the uniform σ_r^T has to be consider equal to the lower of the yield strength of parent metal or weld metal.

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The through thickness profiles presented in figure 6 (d) are also given for two different paths on the weld component (Ai A0, Bi B0).

5-7 Weld T Intersections

The only one information that could be found concerning weld intersection residual stress profiles concerned the stresses at the intersection itself. At any intersection, one weld must be continuous and one weld must be terminated in order to join or cross the other (continuous) weld.

Two treatments are suggested in [12] for the assessment of residual stress:

- a) If the terminating welds is completed first, which is the normal practice, then the intersection has no particular significance and each weld is treated as it normally would be for relevant geometry (i.e. the effect of the intersection should be ignored).
- b) If the terminating weld is completed last, than the residual stress profiles must be assumed to be uniform, tensile through the thickness and of weld metal yield magnitude.

5-8 Repair Welds

The data obtained for repair welds are come from references [2], [10] and [12]. They refer to ferritic, austenitic steels and aluminium for figure 7 (a) and only to ferritic steels for figures 7 (b) 7 (c) 7 (d). If repair welds are short, the through thickness, transverse and longitudinal residual stresses profile are the same.

For repairs that extend to lengths greater than three times the weld thickness, the information presented here should be used with caution. In such cases, the profile for the actual geometry of the weld repair should be considered.

The profiles presented in figures 7 (a), (b) and (d) can be used for any length repair. The profiles presented in figure 7 (c) must be used only for a full length repair.

5-8-1 Longitudinal Residual Stresses

The surface profile is shown in Figure 7(a) is given for different types of materials (Ferritic steel, Austenitic steel and Aluminium). The influence of the plate thickness is taken into account. The calculation of the residual stress decay (r_0 and y_0 parameters) is given for welding conditions and material properties (see appendix 1).

The through thickness profile is presented in Figure 7(b). Through the thickness of the repair, z , the stress should be taken as the greater yield stress of the parent plate, original weld or repair weld. Below the repair, the residual stress reduces linearly with distance to zero at a distance z_0 below the root of the repair. z_0 is related to the heat input of the repair weld and is defined in Figure 7(b). The relevant equations are :

$$s_R^L / s_y^+ (z/t) = 1.0 \text{ for } z < z_r \text{ where } z_r \text{ is the depth of the repair}$$

$$s_R^L / s_y^+ (z/t) = (z_0 + z_r - z)/z_0 \text{ where } z_0 \text{ is given below by}$$

$$z_0 = \sqrt{(122(q/v) / s_y^+)} \text{ where } (q/v) \text{ is in J/mm and } s_y^+ \text{ is in MPa, for } z > z_0 \text{ } s_R^L / s_y^+ (z/t) = 0,0$$

5-8-2 Transverse Residual Stresses

The residual stresses surface profile is shown in 7(c).

The through thickness profile is presented in Figure 7(d). Through the thickness of the repair, z , the stress should be taken as the greater yield stress of the parent plate, original weld or repair weld. Below the repair, the residual stress reduces linearly with distance to zero at a distance z_0 below the root of the repair. z_0 is related to the heat input of the repair weld.

The relevant equations are :

$$s_R^T / s_y^+ (z/t) = 1.0 \text{ for } z < z_r \text{ where } z_r \text{ is the depth of the repair}$$

$$s_R^T / s_y^+ (z/t) = (z_0 + z_r - z)/z_0 \text{ where } z_0 \text{ is given below by}$$

$$z_0 = \sqrt{(122(q/v) / s_y^+)} \text{ where } (q/v) \text{ is in J/mm and } s_y^+ \text{ is in MPa, for } z > z_0 \text{ } s_R^T / s_y^+ (z/t) = 0,0$$

5-9 Post-welded Heat treatment - PWHT

As we will discuss in this paragraph, the utility of PWHT is not yet demonstrated especially if the temperature is less than 400°C. The best results obtained, are for a temperature upper than 500°C and in the range 550°C-650°C. Nevertheless, this kind of treatment need ovens which can accepted big component or a good practise of local heat methods to arise this temperatures, and get deformations which not induce stress greater than those existing.

Leggatt, on submerged-arc welds in 50 mm thick C-Mn-Al-Nb steel, subjected to a range of different PWHT conditions, determines the effects of restraint on the residual stresses in T-butt welds. In this work he found that the maximum residual stresses in the welds, always lay in the longitudinal direction parallel to the weld. The transverse stresses were in general much lower and were found to be relatively insensitive to heat treatment conditions.

The maximum measured residual stresses in the tests were up to 50 MPa greater than the upper bound of the stress relaxation data for corresponding PWHT temperatures and hold times.

The higher stress level in tests was attributed to stress recovery during cooling after PWHT. It was also found that the predicted maximum residual stress after heat treatment (in accordance with BS5500: 1976) represented 30% of the typical room temperature yield stress of the weld metal in the as-welded condition, or 36% of the minimum weld metal yield stress after PWHT.

Zhou et al. studied plate butt welds in A737 steel with a yield stress of 511 MPa. The stress relief applied was a two hour treatment at 550°C. The PWHT was found to reduce the residual stresses to relatively low tensile values, generally in the range 35-70 MPa. The results were used to demonstrate that the stress relief operation was effective and that even high tensile or compressive stresses could be reduce to modest levels in steel through standard stress relief treatments.

The investigation by Fidler into the residual stresses in plate butt welds in CrMoV steel (yield stress 310 MPa) found that the maximum residual stresses measured in the weld metal in the as-welded condition were high (in excess of 300 MPa for the weave weld and 500 MPa for the stringer and horizontal/vertical welds). However, the standard stress relief procedure of one hour per 25 mm thickness was sufficient to reduce residual stresses to less than 50 MPa for both the weave and stringer welds and less than 103 MPa for the horizontal/vertical weld.

Results obtained by Porter Goff and al. for tests on welded plates in Grade 50D steel ($\sigma_y \approx 400$ MPa) with two different filler materials, and PWHT in the range 450 to 550°C showed and confirmed

Leggatt's finding, that residual stresses vary considerably with the filler wire used. The PWHT concession equivalent time formula was broadly supported by the results of a simplified creep model.

Morgan and Gardner studied residual stresses in T-plate butt weld in steel with a yield stress of 376 MPa. It was found that in the longitudinal direction, residual welding stresses were generally tensile in as-welded specimens with values at the weld toe being of yields stress magnitude. However, after stress relieving at 600°C for four hours, the residual stresses were reduced to below 55 MPa even near the weld toe.

As we can see, it is not very easy to know the influence of PWHT. The situation depends on the geometry of the component, the thickness, the temperature of the PWHT, the time at high temperature, the type of heat treatment local or global.

One of the solution recommended by the Health and Safety Executive (HSE) guidance notes is to use PWHT when the hot-spot stress, calculated for the maximum design load, exceeds $0.8 \sigma_y$ of the parent material and when the plate thickness being joined exceeds 40 mm. For other regions, PWHT is recommended when the plate thickness joined exceeds 50 mm. This is why the guidance notes of BS5500 (paragraphs 4.4.3-5) must be used as the basis for PWHT procedures. BS5500 specifies the PWHT temperature and time at temperature for a range of ferritic steels (BS5500 1994 Table 4.4.3.1) and a rate for heating and cooling.

So if we agree with the fact (BS 5500:1976 ; EXXON FFS 1994) that the residual stress for flaws transverse to the weld should be assumed to be 30% of the room temperature yield strength for the material that contains the flaw or 20% and the lower yield of the base metal or weld metal for flaws parallel to the weld. You can get a important decrease of the residual stresses.

The recent work conducted by M. Clergé on the PWHT of a pipeline butt weld (in a thickness of 30 mm and a diameter of 1000 mm) has permitted to obtain longitudinal residual stresses equal to 16% of the lowest yield strength value of the weld metal and base metal on the one hand, and transverse residual stresses equal to 16% of the yield strength of the base metal or equal to 10% of that of the weld metal on the other hand.

However, so as to cover all the industrial application, it was felt reasonable to adopt the values as those proposed in BS 7910-1997 [1] which are 30% of the yield strength of the material for the longitudinal residual stresses and 20% of the lesser of the yield strength of the weld or parent material, for the transverse residual stresses.

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Maryline CLERGE

Post weld heat treatment of a pipeline butt weld.

Ids report n° RT33840, Sintap task 4.3, November 1998

APPENDIX 1**CALCULATION OF THE DIMENSIONS OF YIELDED ZONE****Weld in Thick Material**

$$r_0 = \sqrt{\frac{K}{s_{yp}} \cdot \frac{hq}{n}} \quad [A]$$

r_0 = radius of yield zone, mm

K = a material constant, Nmm/J (see below)

σ_{yp} = yield or 0.2% proof strength of parent metal, N/mm²

Q = ARC POWER = IV , J/SEC

I = current, A

V = voltage, V

v = weld travel speed, mm/sec

η = process efficiency (fraction of arc power entering plate as heat)

EQUATION [A] APPLIES IF $r_0 \leq t$, WHERE t IS THE PLATE THICKNESS. IF $r_0 > t$, THEN THE THIN PLATE FORMULA

Is used (see next section). In general, the thick plate formula is applicable where the weld bead dimensions are small compared with the plate thickness, for example at a multi-pass weld with many passes, or at a small single-pass fillet weld on thick plate.

Weld in Thin Material

$$y_0 = \frac{1.033K}{s_{yp}} \cdot \frac{hq}{vt} \quad [B]$$

In a butt weld, t is the plate thickness. In a T-joint between a base plate of thickness t_b and an attached plate of thickness t_a , t is taken as $(t_b + 0.5 t_a)$. In a corner joint with the same definitions of t_a , t is taken as $0.5 (t_a + t_b)$. All other variables are as defined below Eq. [A].

APPENDIX 1

Equation [B] applies if $y_0 > 1.033 t$. If $y_0 \leq 1.033t$, the thick plate formula is used (see previous section). In general, Eq. [B] is applicable where the weld bead dimensions are comparable with the plate thickness, for example at single pass or two pass butt welds.

Material Constant and Process Efficiency

K is defined as follows :

$$K = 2\alpha E / (e\pi\rho c) \quad [C]$$

Where :

α = coefficient of thermal expansion, $^{\circ}C^{-1}$

E = Young's Modulus, N/mm^2

ρ = density, kg/mm^3

c = specific heat, $J/kg^{\circ}C$

The material properties are taken at ambient temperature ($20^{\circ}C$). Typical values of the relevant properties are listed in Table 2. Taking a typical value of process efficiency, $\eta = 0.8$, gives the following values of $K\eta$:

Ferritic steels, $K\eta = 122 \text{ Nmm/J}$

Austenitic stainless steels, $K\eta = 161 \text{ Nmm/J}$

Aluminium alloys, $K\eta = 131 \text{ Nmm/J}$

Table 2 : Typical material properties

PROPERTIES	FERRITIC STEELS	AUTENITIC STAINLESS STEELS	ALUMINIUM ALLOYS
Coefficient expansion, α , $^{\circ}C^{-1}$	12×10^{-6}	16×10^{-6}	24×10^{-6}
Young's modulus, E, N/mm^2	207 000	193 000	70 000
Volumetric specific heat, ρc , $Jmm^3/^{\circ}C$	0.0038	0.0036	0.0024
$K = 2\alpha E / (e\pi\rho c)$, Nmm/J	153	201	164
$K\eta$, with $\eta = 0.8$	122	161	131

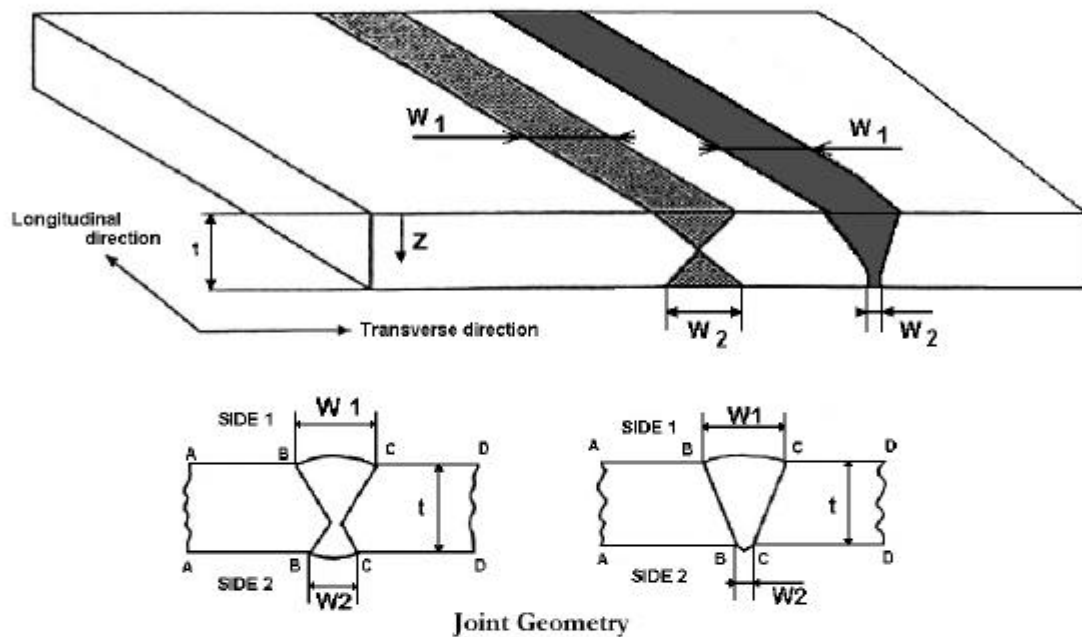
APPENDIX 2

PLATE BUTT WELDS PIPE AND PIPE AXIAL SEAM WELDS

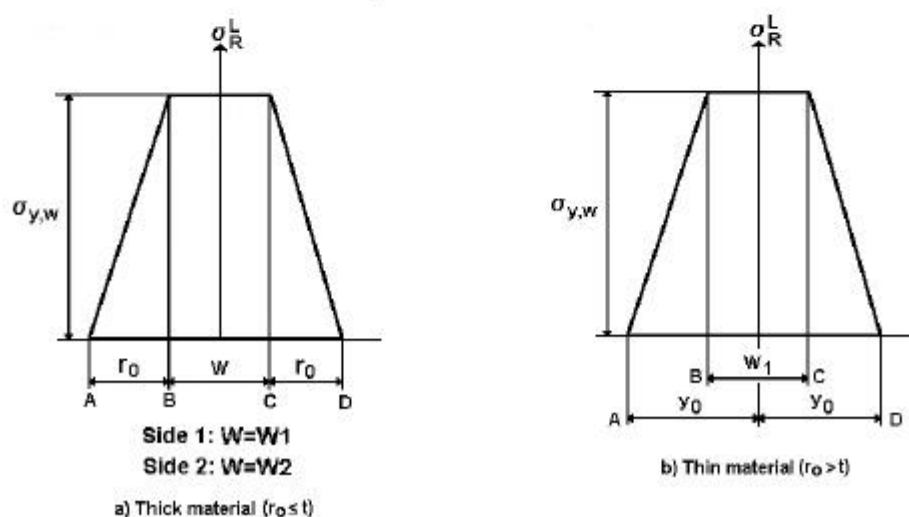
Figure 1

Material : Ferritic, Austenitic steels and Aluminium (only (1a))

1. Geometry



2. Surface Residual Stress Profiles

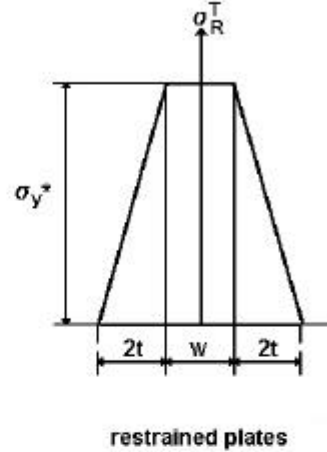
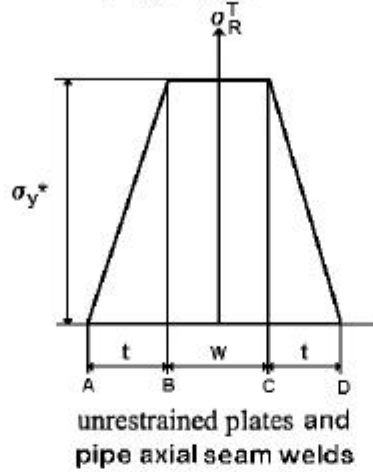
2.1 Longitudinal Residual Stress, σ_R^L (Fig 1a)(For definitions of r_0 , y_0 , see Appendix 1)

APPENDIX 2

Figure 1

2.2 Transverse Residual Stress, σ_R^T (Fig 1 c)

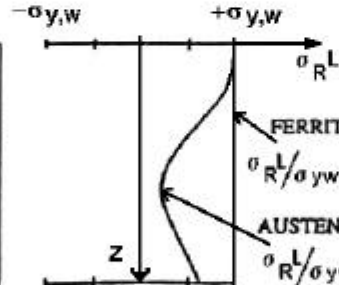
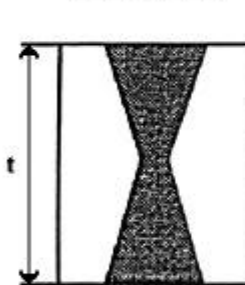
Side 1: $W = W1$
Side 2: $W = W2$



3. Through-thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress, σ_R^L (Fig 1 b)

Distrubution



Equations

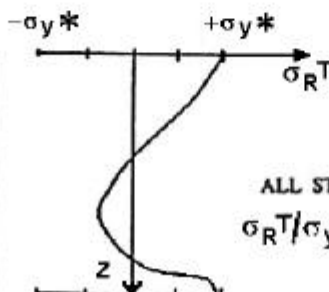
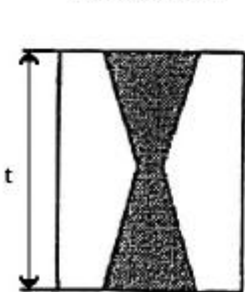
$$\sigma_R^L / \sigma_{yw}(z/t) = 1$$

AUSTENITIC STEELS

$$\sigma_R^L / \sigma_{yw}(z/t) = 0.95 + 1.505(z/t) - 8.287(z/t)^2 + 10.571(z/t)^3 - 4.08(z/t)^4$$

3.2 Transverse Residual Stress, σ_R^T (Fig 1 d)

Distrubution



ALL STEELS

Equations

$$\sigma_R^T / \sigma_{y*}(z/t) = 1.0 - 0.917(z/t) - 14.533(z/t)^2 + 83.115(z/t)^3 - 215.45(z/t)^4 + 244.16(z/t)^5 - 96.36(z/t)^6$$

$$\sigma_{y*} = \text{lower of } \{ \sigma_{yw}, \sigma_{yp} \}$$

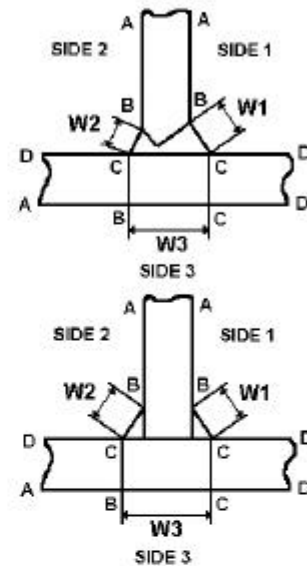
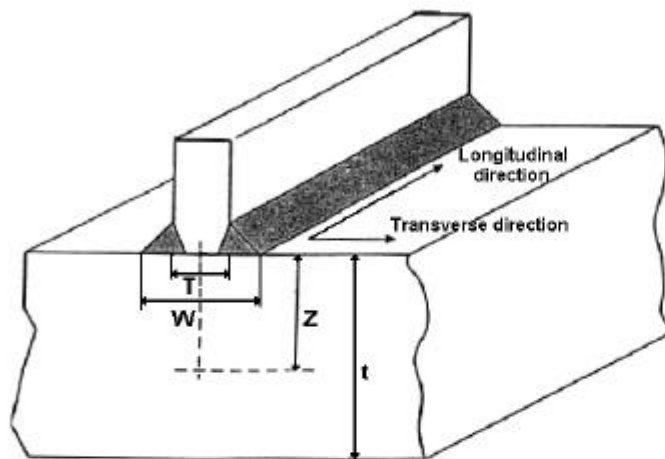
APPENDIX 2

PLATE T-BUTT WELDS

Figure 2

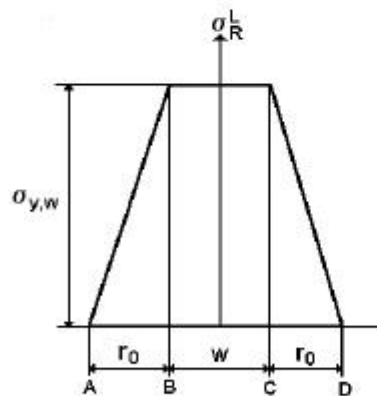
Material : Ferritic, Austenitic steels and Aluminium (only (2 a))

1. Geometry

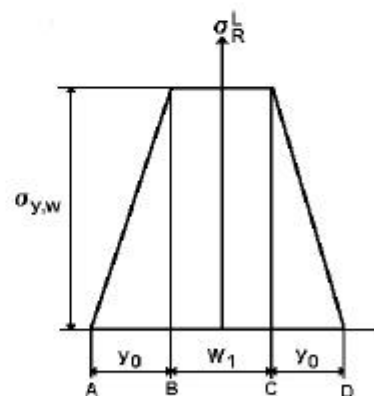


Joint Geometry

2. Surface Residual Stress Profiles

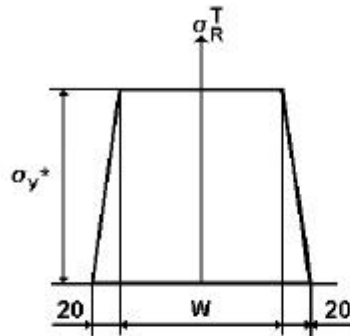
2.1 Longitudinal Residual Stress, σ_R^L (fig 2a)Side 1 : $w = w_1$ Side 2 : $w = w_2$

Side 3 : not applicable

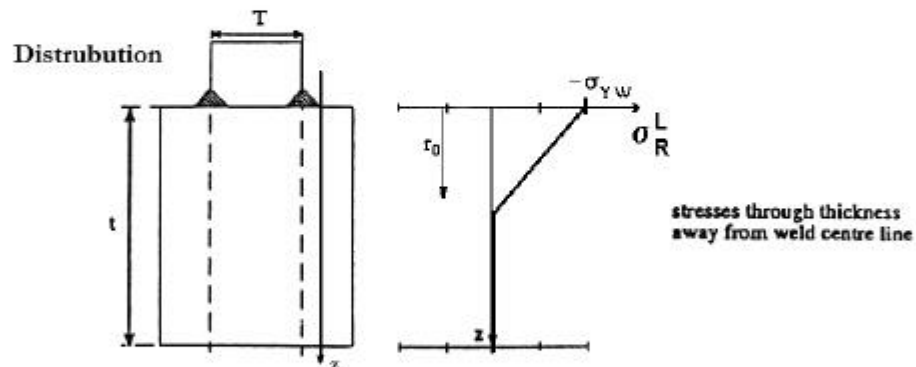
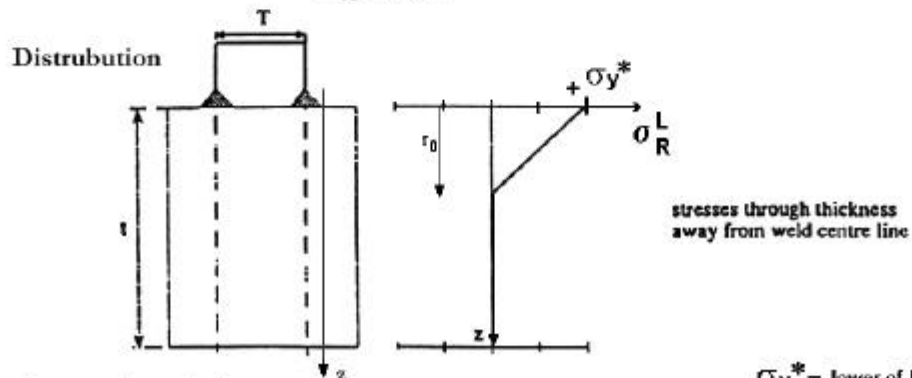
a) Thick material ($r_0 \leq t$)Side 1 : $w = w_1$, $\sigma_y = \sigma_{yw}$ Side 2 : $w = w_2$, $\sigma_y = \sigma_{yw}$ Side 3 : $w = w_3$, $\sigma_y = \sigma_{yp}$ b) Thin material ($r_0 > t$)(For definitions of r_0 , y_0 , see Appendix 1)

APPENDIX 2

Figure 2

2.2 Transverse Residual Stress, σ_R^T (fig 2c)

3. Through-thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress σ_R^L (fig 2b)3.2 Transverse Residual Stress σ_R^T (fig 2d)(For definitions of r_0 , y_0 , see Appendix 1)

$$\sigma_y^* = \text{lower of } \{\sigma_{yw}, \sigma_{yp}\}$$

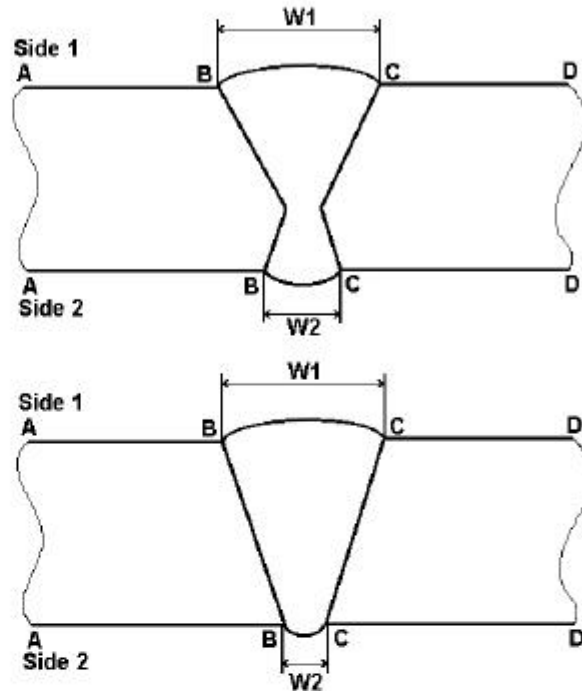
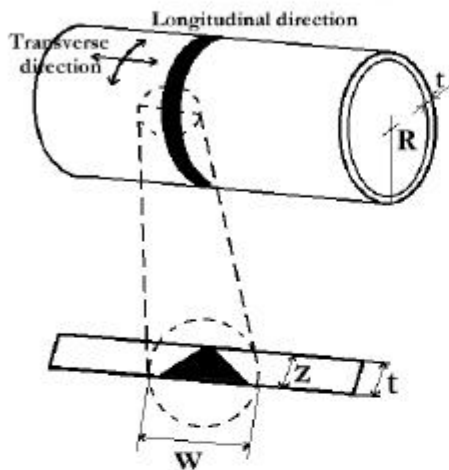
APPENDIX 2

PIPE BUTT WELDS

Figure 3

Material : Ferritic, Austenitic steels and Aluminium (only (3a))

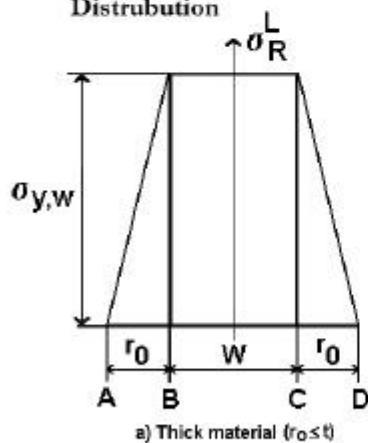
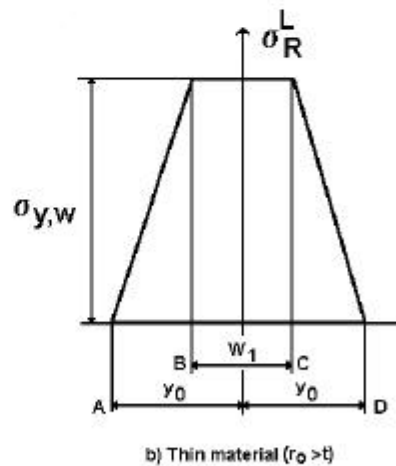
1. Geometry



2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, σ_R^L (fig 3a)

Distribution

Side 1: $W = W_1$
Side 2: $W = W_2$ (For definitions of r_0, y_0 , see Appendix 1)2.2 Transverse Residual Stress, σ_R^T (fig 3c)Use uniform $\sigma_R^T = \sigma_y^*$

$$\sigma_y^* = \text{lower of } (\sigma_{y,w}, \sigma_{y,p})$$

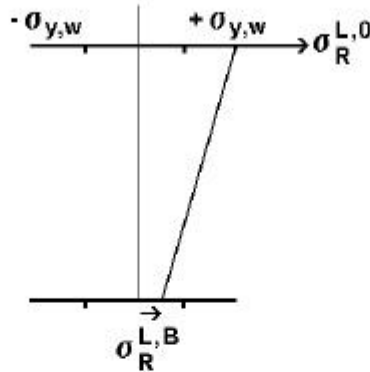
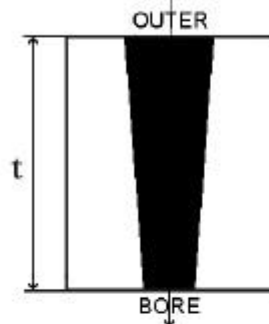
APPENDIX 2

Figure 3

3. Through Thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress, σ_L^R (fig 3b)

Distribution



Equations

$$\sigma_R^{L,B} = A_b \sigma_{y,w}$$

Where: $A_b = 1$

$$A_b = 1 - 0.0143 (t - 15)$$

$$A_b = 0$$

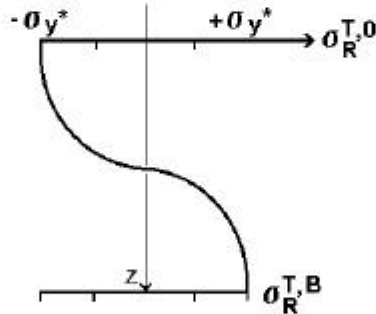
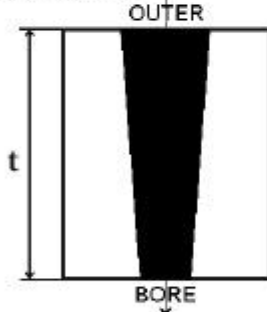
$$0 < t \leq 15 \text{ mm}$$

$$15 \text{ mm} < t \leq 85 \text{ mm}$$

$$t > 85 \text{ mm}$$

3.2 Transverse Residual Stress, σ_T^R (fig 3d)

Distribution



Ferritic high heat input

Equations

FERRITIC STEELS

For Low heat inputs $(q/v)t < 60 \text{ J/mm}^2$ and $\sigma_R^{T,0}/\sigma_y^* = -0.5 - 0.0083(q/v)t$

$$\sigma_R^T = \sigma_R^{T,0} (1.0 - 3.29(z/t) - 26.09(z/t)^2 + 73.16(z/t)^3 - 45.72(z/t)^4)$$

For High heat inputs $(q/v)t > 60 \text{ J/mm}^2$ and $\sigma_R^{T,0} = -1.0$

$$\sigma_R^T = \sigma_R^{T,0} \cos(\pi z/t); z \text{ measured from outer surface}$$

AUSTENITIC STEELS

$$t < 25 \text{ mm}$$

$$t \leq 7 \text{ mm} \quad \sigma_R^T = 1.219 \sigma_y^* \left[\frac{2z}{t} - 1 \right]$$

$$7 \text{ mm} < t \leq 25 \text{ mm} \quad \sigma_R^T = (1.5884 - 0.05284 t) \sigma_y^* \left[\frac{2z}{t} - 1 \right]$$

$$t \geq 25 \text{ mm}$$

$$\sigma_R^T = \sigma_R^{T,B} (0.27 - 0.91(z/t) - 4.93(z/t)^2 + 8.60(z/t)^3 - 2.03(z/t)^4)$$

For definition of $\sigma_R^{T,B}$ see paragraph 5.3.2

$$\sigma_y^* = \text{lower of } (\sigma_{yw}, \sigma_{yp})$$

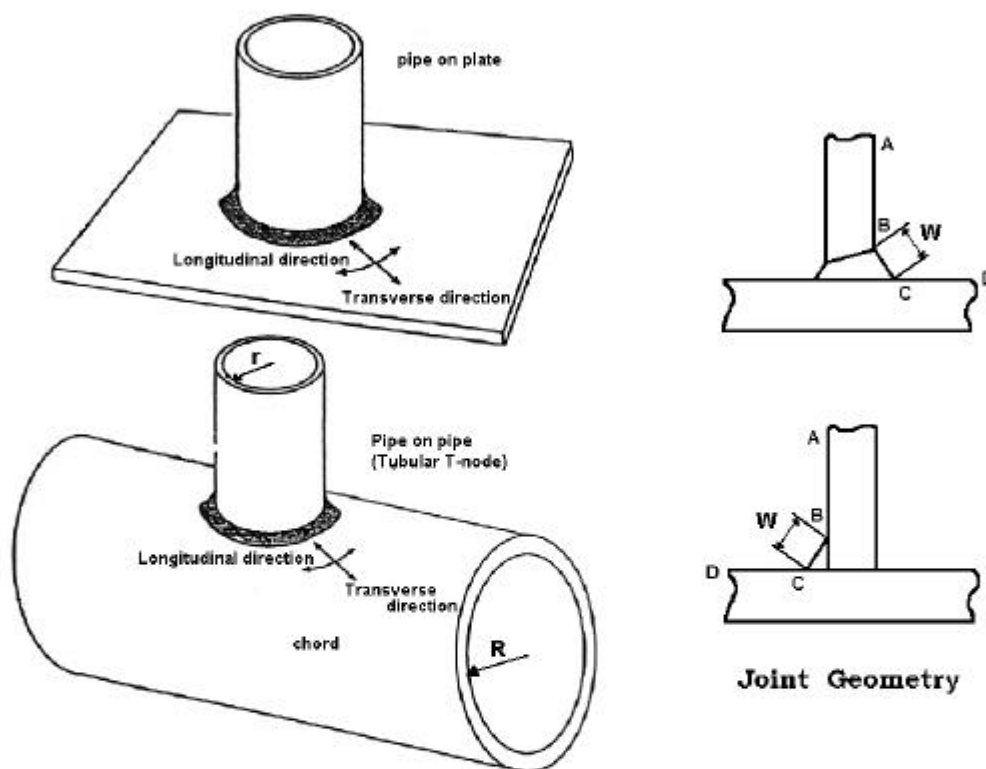
APPENDIX 2

PIPE T-BUTT WELDS

Figure 4

Material : Ferritic, Austenitic steels (caution for (4b),(4c),(4d)) and Aluminium (only (4a))

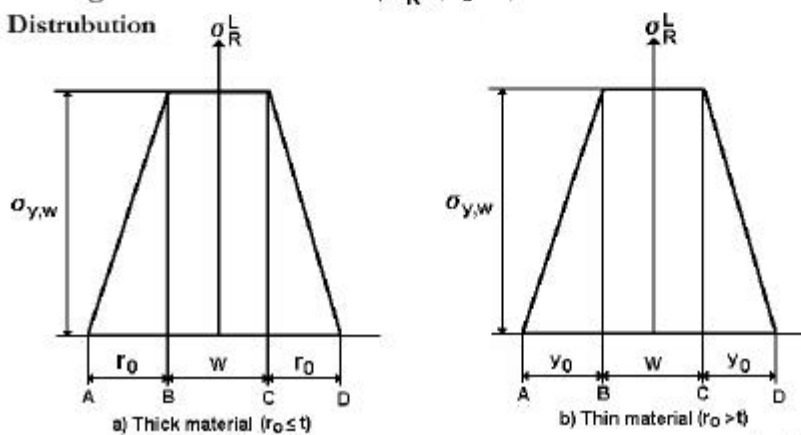
1. Geometry



2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, σ_R^L (fig 4a)

Distribution

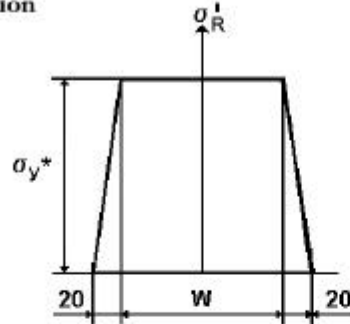
(For definitions of r_0 , y_0 , see Appendix 1)

APPENDIX 2

Figure 4

2.2 Transverse Residual Stress, σ_R^T (fig 4c)

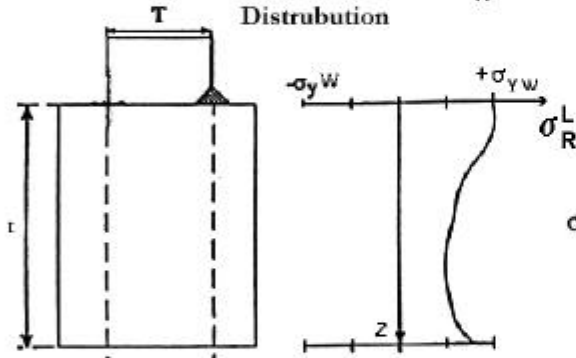
Distrubution



3. Through Thickness Profiles

3.1 Longitudinal Residual Stress, σ_R^L (fig 4b)

Distrubution

stress through thickness
away from weld centre line

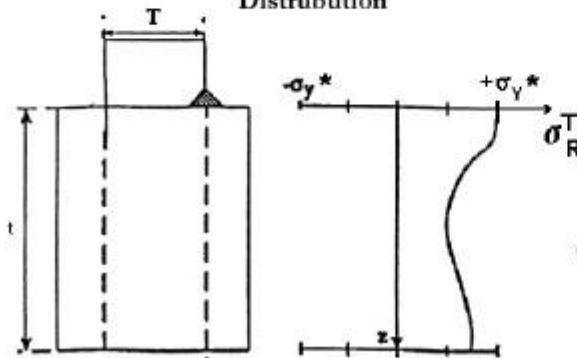
Equations

FERRITIC STEELS

$$\sigma_R^L / \sigma_{yw} (z/t) = 1.025 + 3.478 (z/t) - 27.861 (z/t)^2 + 45.788 (z/t)^3 - 21.8 (z/t)^4$$

3.2 Transverse Residual Stress, σ_R^T (fig 4d)

Distrubution

stress through thickness
away from weld centre line

Equations

FERRITIC STEELS

$$\sigma_R^T / \sigma_{y*} (z/t) = 0.97 + 2.327 (z/t) - 24.125 (z/t)^2 + 42.485 (z/t)^3 - 21.087 (z/t)^4$$

$$\sigma_{y*} = \text{lower of } (\sigma_{yw}, \sigma_{yp})$$

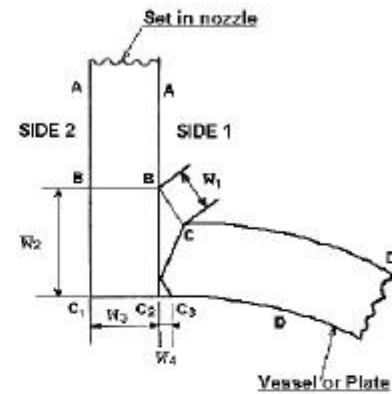
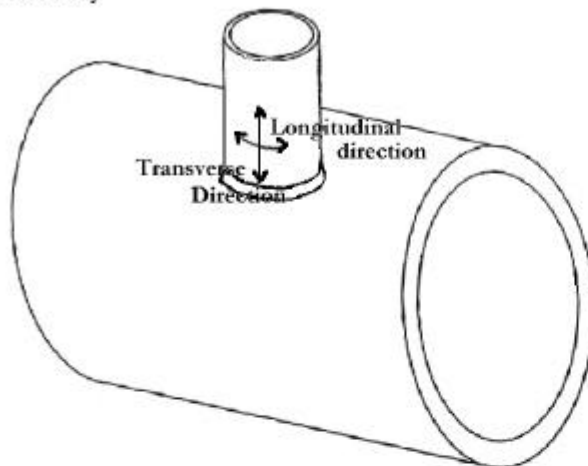
APPENDIX 2

SET IN NOZZLE

Figure 5

Material : Ferritic , Austenitic steels and Aluminium

1. Geometry

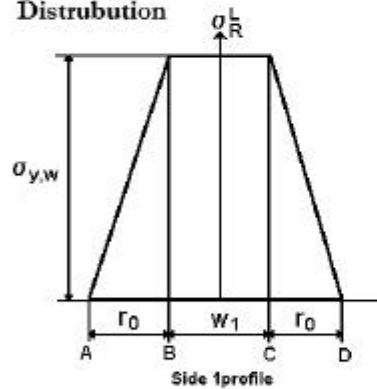
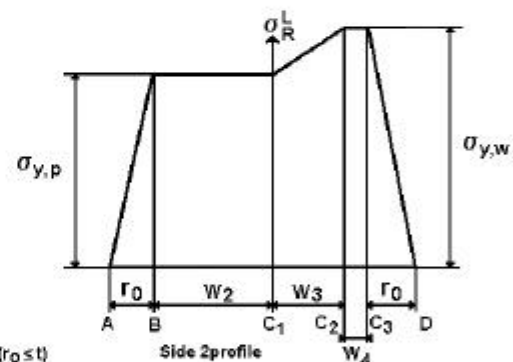


Joint Geometry

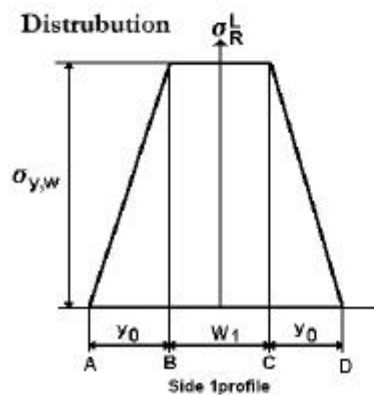
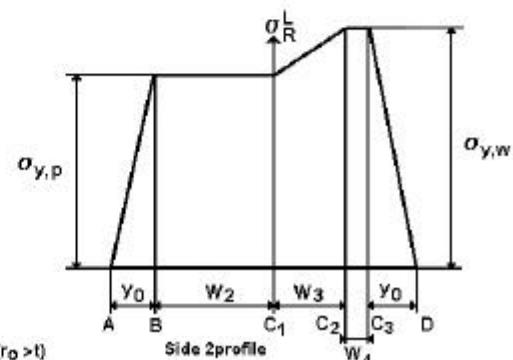
2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, σ_R^L (fig 5a)

Distribution

a) Thick material ($r_0 \leq t$)

Distribution

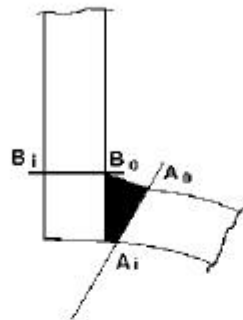
b) Thin material ($r_0 > t$)(For definitions of r_0 , y_0 , see Appendix 1)

APPENDIX 2

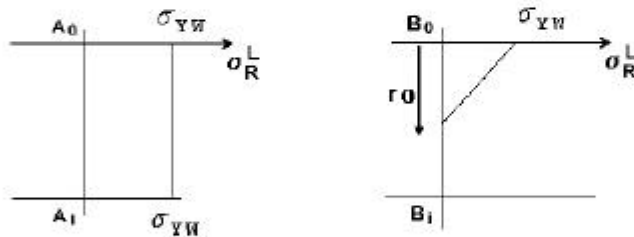
Figure 5

2.2 Transverse Residual Stress, σ_R^T (fig 5c)Use uniform $\sigma_R^T = \sigma_Y^*$

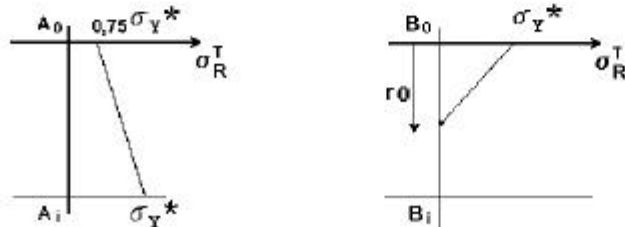
3. Through Thickness Profiles

3.1 Longitudinal Residual Stress, σ_R^L (fig 5b)

Distribution

3.2 Transverse Residual Stress, σ_R^T (fig 5d)

Distribution

(For definitions of r_0 , y_0 , see Appendix 1)

$$\sigma_Y^* = \text{lower of } (\sigma_{YW}, \sigma_{YP})$$

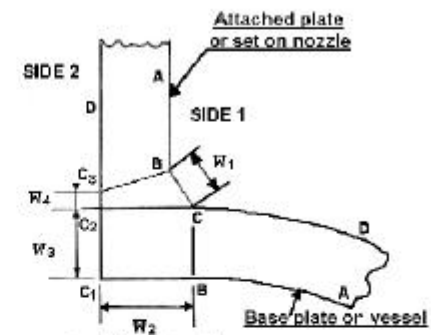
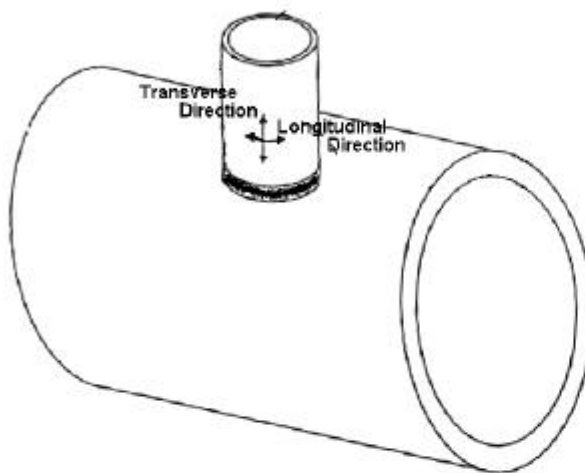
APPENDIX 2

SET ON NOZZLE

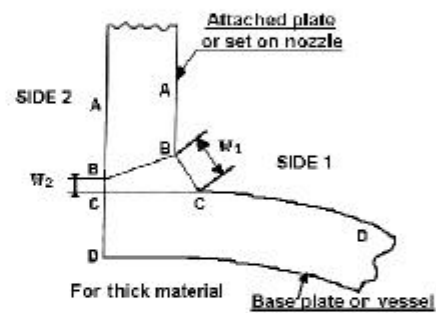
Figure 6

Material : Ferritic ,austenitic steels and Aluminium

1. Geometry



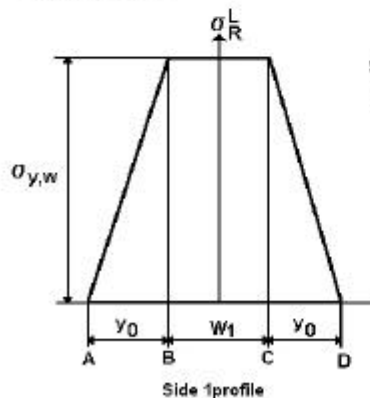
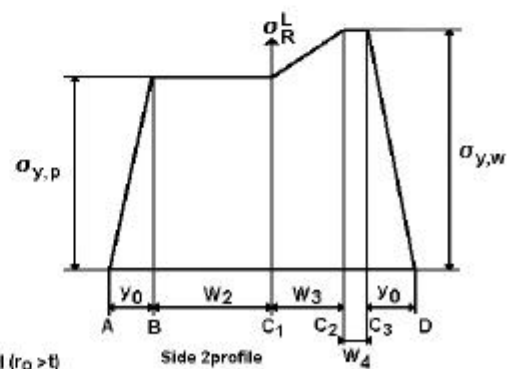
For thin material



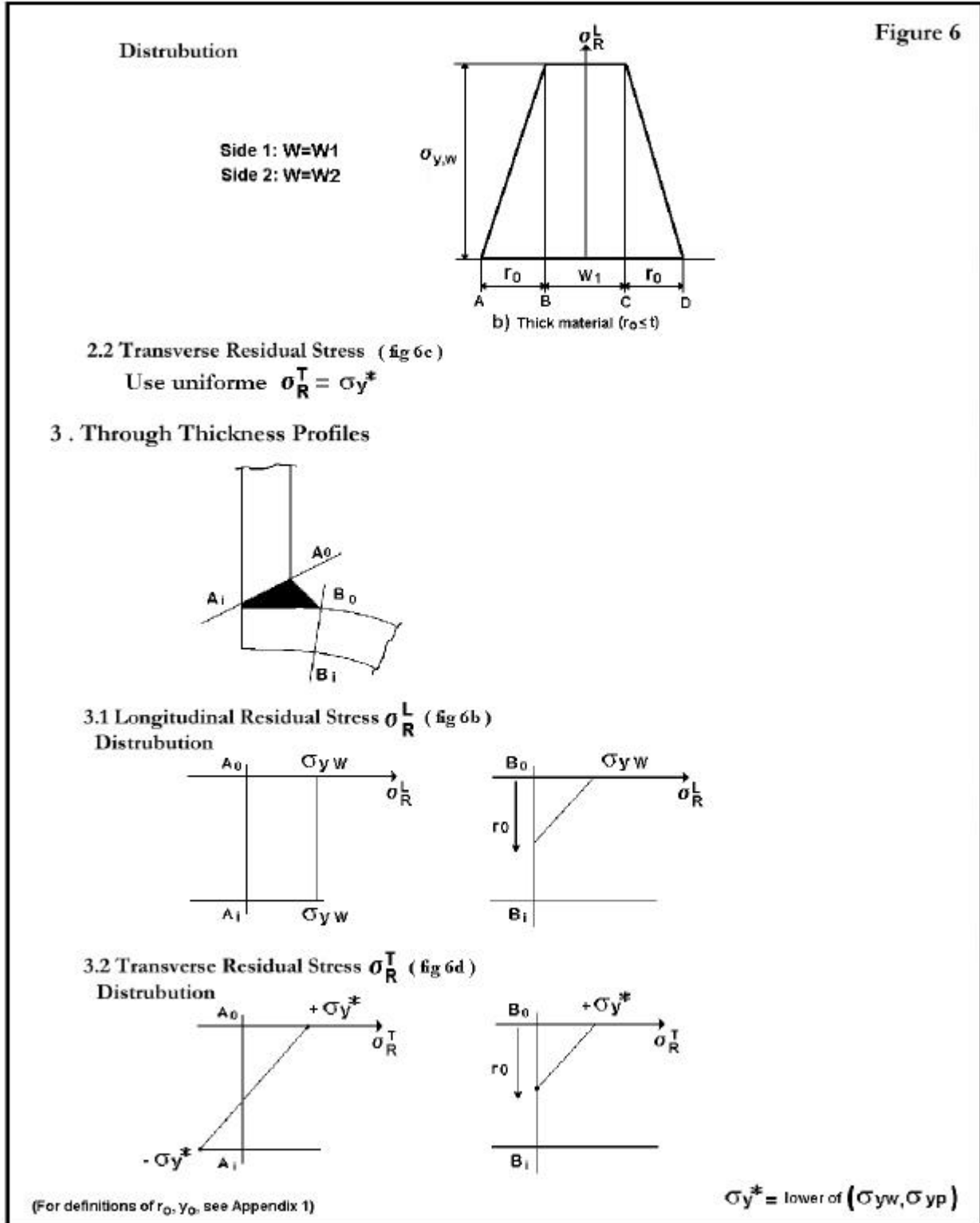
For thick material

Joint Geometry

2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, σ_R^L (fig 6a)
DistribuitionSide 1: $W=W1$
Side 2: $W=W2$ a) Thin material ($r_0 > t$)(For definitions of r_0 , y_0 , see Appendix 1)

APPENDIX 2



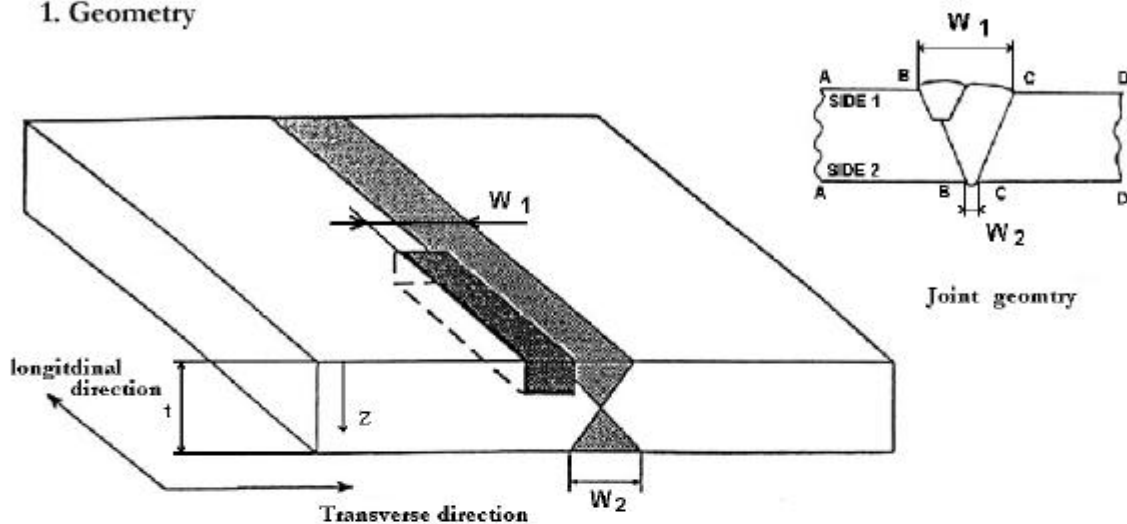
APPENDIX 2

REPAIR WELDS

Figure 7

Material : Ferritic austenitic steels and Aluminium (7a)
 Ferritic steels (7b),(7c),(7d)

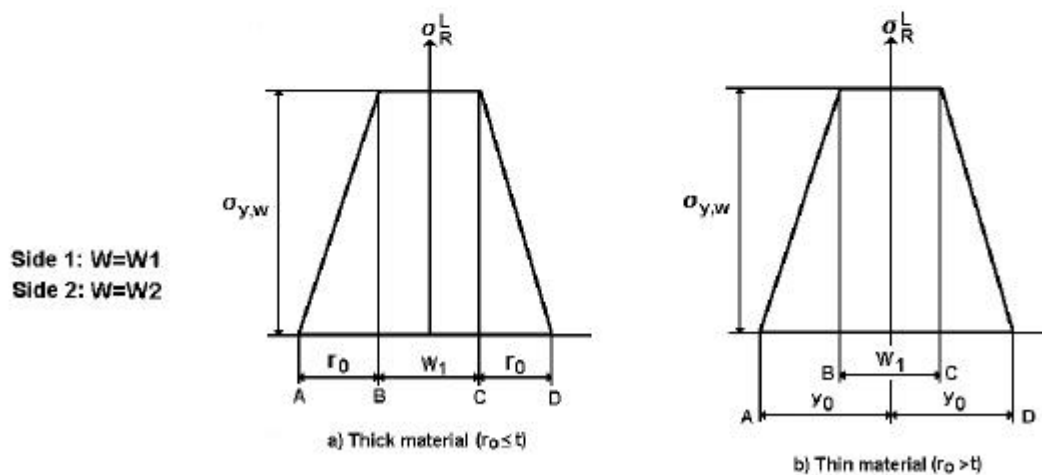
1. Geometry



2. Surface Residual Stress Profiles

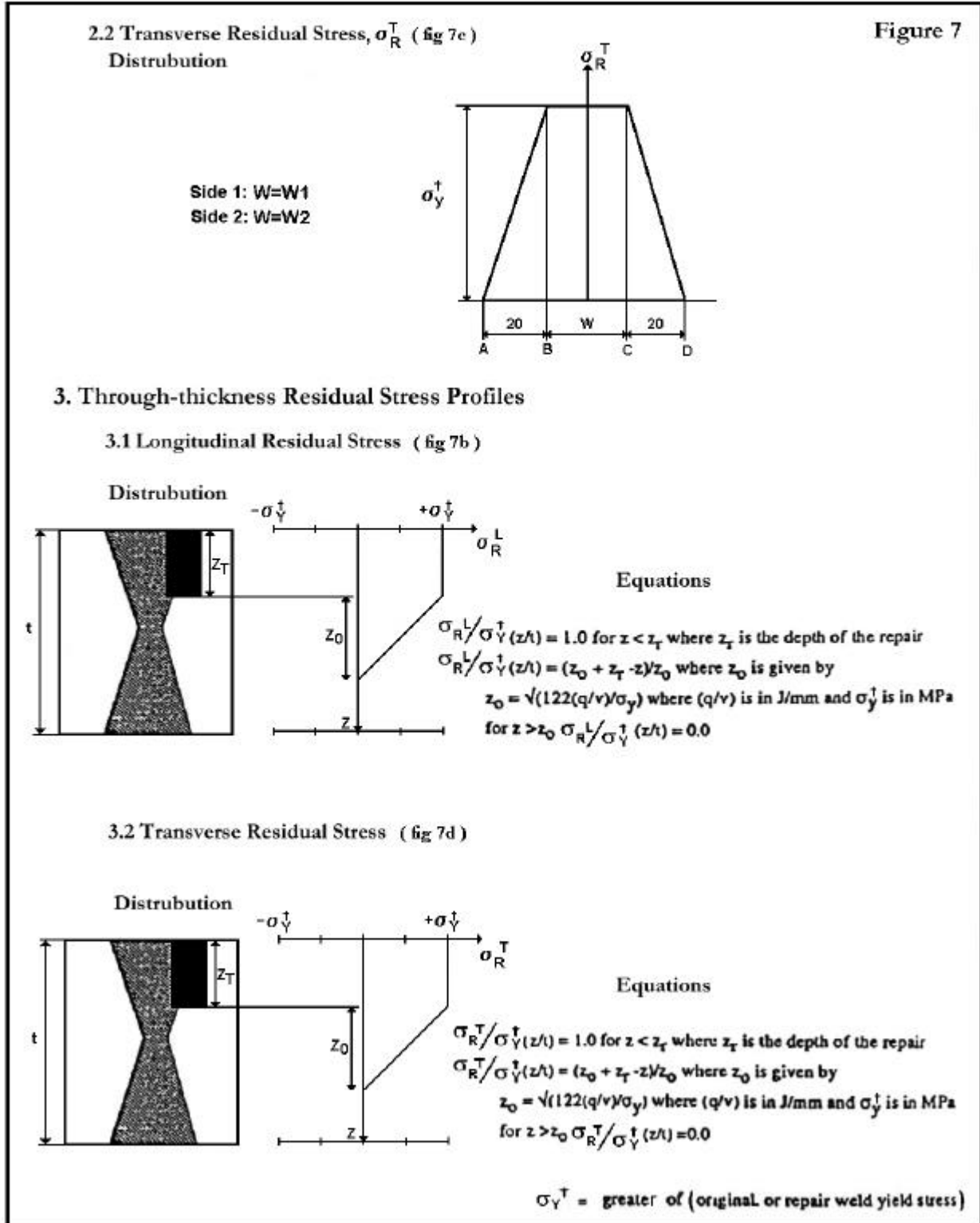
2.1 Longitudinal Residual Stress, σ_R^L (fig 7a)

Distribution



(For definitions of r_0 , y_0 , see Appendix 1)

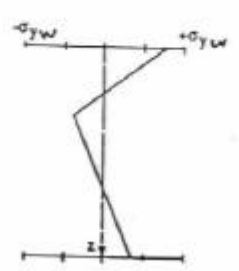
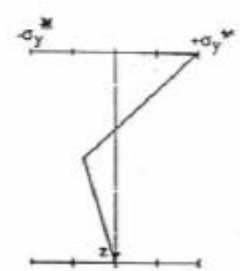
APPENDIX 2



APPENDIX 3

APPENDIX 3

Through thickness residual stress profiles including a polynomial function

JOINT GEOMETRY	LONGITUDINAL	TRANSVERSE
PLATE T BUTT WELDS	FERRITIC STEELS $\sigma_R^L / \sigma_{yw} \alpha_z(z/h) = 0.75 - 3.34(z/h) \quad z/h < 1/2$ $\sigma_R^L / \sigma_{yw} \alpha_z(z/h) = -0.66 + (z/h) \quad z/h > 1/2$ 	FERRITIC STEELS $\sigma_R^T / \sigma_y^* \alpha_z(z/h) = 1 - 2.66(z/h) \quad z/h < 1/2$ $\sigma_R^T / \sigma_y^* \alpha_z(z/h) = -0.66 + 0.66(z/h) \quad z/h > 1/2$ 

Surface residual stress profiles including a polynomial function

JOINT GEOMETRY	LONGITUDINAL
PLATE BUTT WELDS AND PIPE SEAM WELDS	
PLATE T BUTT WELDS	

APPENDIX 3

PIPE BUTT WELDS	
PIPE T BUTT WELDS	
REPAIR WELDS	

Through thickness residual stress profiles including a polynomial function

<i>JOINT GEOMETRY</i>	<i>LONGITUDINAL</i>	<i>T RANSVERSE</i>
PLATE T BUTT WELDS		