Annex C

Residual Stress Profiles

C.1 Symbols

Within this section, the following symbols are used with the dimensions specified below.

$\tilde{Q}$ Weld pass heat input into workpiece per unit length per unit thickness, $\tilde{Q} = \eta[(q/v)/t], J/mm^2$

q Weld torch arc power (current x closed circuit voltage) J/sec

R Mean radius of pipe (or radius of chord for Pipe T-Butt), mm

r Radius of brace in pipe T-Butt, mm

r_0 Dimensions of the yield zone for a thin plate, mm

T Plate (or chord) thickness for T weld joint, mm

t Plate or pipe thickness (or thickness of brace for Pipe T-Butt), mm

v Weld torch advance rate, mm/sec

W Width of the weld at surface, mm

y_0 Dimensions of the yield zone for a thick plate, mm

z Position through-thickness, mm

z_r Depth of a repair weld, mm

z_0 Size of yield zone below repair weld, mm

δ Heat input sinusoid correlation factor for pipe butt weld Level 3 longitudinal stress

φ Heat input bending correlation factor for pipe butt weld Level 3 transverse stress

η Weld process efficiency

θ Heat input sinusoid correlation factor for pipe butt weld Level 3 transverse stress

σ_y Typical[1] room temperature yield strength of material, MPa. For austenitic material, the typical 1% proof stress should be used. For ferritic material the typical yield point or typical 0.2% proof stress is appropriate

σ_y^* Lower of $(\sigma_{yp}, \sigma_{yw})$, MPa

σ_y^+ Greater of $(\sigma_{yp}, \sigma_{yw})$, MPa

σ_{yp} Parent metal typical yield strength, MPa

σ_{yw} Weld metal typical yield strength, MPa

σ_R^L Longitudinal residual stress, MPa

$\sigma_R^{L,O}$ Longitudinal residual stress at outer surface, MPa

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[1] Typical rather than lower bound room temperature yield strength properties should be used. A typical value is defined to be a mean estimate of the yield strength, as used to construct the failure assessment diagram.

$\sigma_R^{L,B}$ Longitudinal residual stress at bore surface, MPa

σ_R^{T} Transverse residual stress, MPa

$\sigma_R^{T,O}$ Transverse residual stress at outer surface, MPa

$\sigma_R^{T,B}$ Transverse residual stress at bore surface, MPa

C.2 Introduction

This section presents a compendium of recommended residual stress profiles for a range of different configurations of as-welded structural weldments. Section II.7 distinguishes between three types of through-wall residual stress profile (Levels 1–3). Level 1 profiles readily enable an initial conservative assessment of a defect to be made by assuming an uniform, tensile residual stress field equal in magnitude to the maximum yield stress of the plate or weld material (Section II.7.5.1). Level 2 profiles provide a more detailed but conservative through-wall characterisation. Level 3 profiles represent a more realistic estimate of the specific weld through-wall residual stress distribution based on experimental measurements combined with detailed analysis. A majority of the residual stress profiles recommended here are essentially upper bounds to available measured and predicted residual stress data, that is they are classified as Level 2 in Section II.7. Although these through-wall profiles do not represent realistic self-balancing stress distributions, they do give a starting point in the quantification of residual stresses that is less conservative than a Level 1 assumption, in almost all cases. More realistic residual stress through-wall profiles (Level 3) for austenitic stainless steel pipe butt welds are included in Appendix C.2.

A compendium of weld residual stress profiles supporting R6 assessments was first compiled in 1991 [C.1]. Since then the compendium has been continually reviewed and updated [C.2], [C.3] and [C.4]. The review performed under the EC funded SINTAP project [C.4] provided a consensus of residual stress profiles based on [C.3] and BS7910 [C.5]. Subsequently, the recommended distributions for ferritic and austenitic steel pipe girth welds have been revised in BS7910 Amendment No.1 [C.6]. A further literature review has been performed since the release of [C.4] and [C.6], and the profiles for ferritic plate butt welds and pipe butt welds updated. This section provides the latest recommended residual stress profiles for the fracture assessment of defects in welded structures.

Following a discussion of stress categorisation in Section C.3, and the methodology used to develop the Level 2 profiles in Section C.4, the compendium of upper bound profiles is set out in Sections C.5-13, supported by figures for each geometry considered. The geometries considered are:

C.5 Plate Butt and Pipe Seam Welds

C.6 Plate T-Butt Welds

C.7 Pipe Butt Welds

C.8 Pipe T-Butt Welds

C.9 Set-in Nozzles

C.10 Set-on Nozzles

C.11 Repair Welds

C.12 Transition Welds

C.13 Weld T-Intersections

For some of these profiles, it is necessary to calculate the parameters of the yielded zone at the weld and these calculations are set out in Appendix C.1. Some more realistic through-wall profiles (Level 3) for austenitic stainless steel pipe butt welds are included in Appendix C.2. Section C.14 contains references cited in the text. However, there is a much more extensive bibliography on which the profiles are based and, for completeness, this is included here in Appendix C.3.

C.3 Stress Categorisation

The literature surveys undertaken for the assembly of this compendium indicate that residual stress distributions are made up of two components. The first is directly attributable to the welding process, arising due to the thermal contractions and phase changes that occur in the weldment. The other component arises due to mismatches and restraints within the structure itself. This, second component is obviously variable from case to case.

Section I.5 draws attention to the classification of stresses for use in assessments and requires that all stresses should be classified into primary, σ^p, and secondary, σ^s, stresses. Primary stresses are those which contribute to collapse, such as applied loads or pressures. If there is significant elastic follow-up within a structure, then some displacement-controlled stresses must also be classified as primary stresses. Secondary stresses are those that are self equilibrating across the section, that is, the net force or bending moment across a section due to the secondary stresses is zero.

Wherever possible, the residual stress distributions given in this section exclude long-range structural restraint effects. If long-range residual stresses that exhibit significant elastic follow-up are present, they must be considered separately, and, if necessary, treated as primary stresses. Section II.7.4.1 provides detailed guidance on the classification of weld residual stresses for fracture assessment.

C.4 Methodology Used to Produce the Compendium

In developing the Level 2 profiles summarised below in Sections C.5-13, data obtained for each geometry were fitted to upper bound tensile profiles. As a result, the quoted profiles are not, in general, self-equilibrating across the weld section. However, the individual profiles from which the sum of the data was obtained were self equilibrating so that the profiles given in this compendium may be treated as conservative estimates of secondary stresses in an assessment.

In Sections C.5-13, equations for the upper bound fits are presented, but, due to the quantity and scatter of data, the original data points are not shown.

The residual stress profiles are given as transverse stresses, σ_R^T (stresses normal to the weld run) and longitudinal, σ_R^L (stresses parallel to the weld run). The variation of stresses with through wall distance and normal distance from the weld centre-line are shown. Stresses acting in the through thickness direction are assumed to be negligible.

Two approaches for defining Level 2 residual stress profiles are provided in Sections C.5-13 depending on the available information about welding conditions.

1) If the welding conditions are known or can be estimated, then residual stress profiles given in this section may be used in association with the size parameters of the plastic zone (r_0, y_0) given in Appendix C.1.

2) If the welding conditions are unknown, then the given polynomial functions should be used.

The as-welded Level 2 residual stress profiles for ferritic steel joints are valid for the range of thickness, yield strength and heat input given in Table C.1.

Longitudinal residual stresses are normalised with respect to the greater of the typical room temperature yield strengths of the weld or plate materials, σ_y^+. Transverse residual stresses are normalised with respect to the lower of the typical room temperature yield strengths of the weld or plate materials, σ_y^*, with the exception of the three cases listed below:

(i) defects at repair welds;

(ii) defects at weld intersections;

(iii) shallow defects with a depth no greater than one weld run.

In these cases, transverse residual stresses for fracture assessment should be based on the greater of the parent or weld metal yield strength.

When interpreting the profiles for austenitic steels, it is conservative to use the room temperature 1% proof stress properties. This allows for material work hardening and the large variability observed in 0.2% proof stress properties for austenitic materials.

Once the room temperature residual stress distribution has been defined, Section II.7.3 describes how to account for mechanical stress relief, the assessment temperature and historical operation at high temperatures in the fracture assessment.

The through thickness stress profiles are normalised with respect to plate thickness.

For each geometry considered, there are associated Figures (a) to (d) which 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.

A schematic illustration of the weld geometry is shown in each figure, which illustrates the longitudinal and transverse directions and various dimensional parameters that are used in Figures (a) to (d).

For all geometries, the figures, in conjunction with the comments in the appropriate part of the following text, should provide sufficient information to generate a conservative residual stress profile.

For fracture assessment where adequate reserve margins are not obtained using the upper bound Level 2 profiles recommended in Sections C.5-13, more detailed (Level 3) residual stress distributions should be determined, see Section II.7.5.3. For austenitic stainless steel pipe butt welds, Level 3 through-wall profiles can be estimated using the formulation described in Appendix C.2. For other weld geometries, the references listed in Appendix C.3 can be consulted to help characterise and substantiate more realistic Level 3 profiles for the specific welded joint, materials and welding conditions of interest.

C.5 Plate Butt and Pipe Seam Welds.

The depth, z, used to define the through-wall profiles, is measured from the surface on which the last bead is deposited.

C.5.1 Longitudinal Residual Stresses

Surface profiles based on the recommendations of Leggatt [C.7] are shown in Figure C.1(a) for ferritic, austenitic and aluminium material, and for single and double sided welds. The calculation of the parameters

r_0 and y_0 is given in Appendix C.1. If the weld is asymmetric, side one is the side with the widest weld face (i.e. $W_1 > W_2$).

The through thickness profile is shown in Figure C.1(b) for ferritic and austenitic steels. The recommended profiles are:

Ferritic Steels:

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

Austenitic Steels

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

C.5.2 Transverse Residual Stresses

The surface profiles are shown in Figure C.1(c). For pipe seam welds and unrestrained plates the profile is based on the recommendations of Leggatt [C.7]. For restrained plates the profile of Mathieson [C.1] is retained.

The recommended transverse through thickness profile is given in Figure C.1(d). This profile is an upper bound to data obtained from both ferritic and austenitic steels.

Ferritic and Austenitic Steels:

$$\sigma_R^T / \sigma_y^*(z/t) = 1 - 0.917(z/t) - 14.533(z/t)^2 + 83.115(z/t)^3 - 215.45(z/t)^4 + 244.16(z/t)^5 - 96.36(z/t)^6$$

C.6 Plate T-Butt welds

C.6.1 Longitudinal Residual Stresses

The longitudinal surface profiles recommended by Leggatt [C.7] are shown in Figure C.2(a) for ferritic, austenitic and aluminium material and for two different weld preparations. The calculation of the parameters r_0 and y_0 is given in Appendix C.1. If the weld is asymmetric, side one is the side with the widest weld face (i.e. $W_1 > W_2$).

The through thickness profile is shown in Figure C.2(b), where the parameter r_o is calculated according to Appendix C.1. If the welding conditions are unknown, then the following profile may be used for ferritic steel:

Ferritic Steel

$$\sigma_R^L / \sigma_{yw}(z/t) = 0.75 + 4.766(z/t) - 26.696(z/t)^2 + 38.11(z/t)^3 - 16.82(z/t)^4$$

C.6.2 Transverse Residual Stresses

For transverse surface stresses the profile of Mathieson [C.1] is still retained. Figure C.2(c) shows the recommended surface profile, where W is defined in Figure C.2(a).

Figure C.2(d) shows the through wall distribution, where the parameter r_0 is calculated according to Appendix C.1.

C.7 Pipe Butt Welds

There have been a number of proposals in structural integrity procedures and published compendia for the through-wall residual stress profiles to use in fracture assessments for pipe butt welds. The upper bound (Level 2) residual stress profiles recommended here for stainless steel welds are supported by extensive measurements and numerical predictions [C.8]. More realistic through-wall residual stress profiles (Level 3) are defined in Appendix C.2 for improved fracture assessments of stainless steel pipe welds.

C.7.1 Longitudinal Residual Stresses

The longitudinal surface profiles of Leggatt [C.7] for ferritic steel, austenitic steel and aluminium are recommended for single-sided and double-sided welds, see Figure C.3(a). The calculation of the parameters r_0 and y_0 is given in Appendix C.1. If the weld is asymmetric, side one is the side with the widest weld face (i.e. W_1>W_2).

The longitudinal through wall residual stress distribution for both ferritic and austenitic steels is given as a linear profile defined by $\sigma_R^{L,O}$ at the outer surface and $\sigma_R^{L,B}$ at the bore, see Figure C.3(b), where the surface values are defined by

$$\sigma_R^{L,O} = \sigma_{yw}$$

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

where: $A_b = 1$ $\quad 0<t<15$mm

$A_b = 1 - 0.0143(t-15)$ $\quad 15 \text{ mm} < t \leq 85 \text{ mm}$

$A_b = 0$ $\quad t > 85$ mm

For a pipe thickness of less than 15mm, 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 85mm.

C.7.2 Transverse Residual Stresses

No detailed profiles are proposed for surface transverse residual stresses because there are insufficient data available and they are geometry sensitive. In the interim, a uniform stress σ_R^T equal to σ_y^*, the lower of the parent or weld metal yield strength, should be considered.

Through-thickness transverse residual stress profiles recommended for ferritic and austenitic steel single-sided welds (made from the outside) are depicted in Figure C.3(d). The profiles are defined in terms of the fractional distance from the bore, z/t, and are dependent on the weld electrical heat input per unit run length per unit thickness, [(q/v)/t], for the largest weld run where:

q = welding torch arc power (current x closed circuit voltage), J/sec

v = weld torch advance rate, mm/sec

z = distance from inner surface of pipe, mm

t = pipe thickness, mm

For high heat input ferritic and austenitic steel welds where $[(q/v)/t] > 120$ J/mm^2

$$\sigma_R^T = \sigma_y^*[1.00 - 0.22(z/t) - 3.06(z/t)^2 + 1.88(z/t)^3]$$

For medium heat input ferritic steel welds where 50 J/mm^2 $< [(q/v)/t] \leq 120$ J/mm^2

$$\sigma_R^T = \sigma_y^*[1.00 - 4.43(z/t) + 13.53(z/t)^2 - 16.93(z/t)^3 + 7.03(z/t)^4]$$

For low heat input ferritic steel welds where $[(q/v)/t] \leq 50$ J/mm^2, and for medium/low heat input austenitic steel welds where $[(q/v)/t] \leq 120$ J/mm^2

$$\sigma_R^T = \sigma_y^*[1.00 - 6.80(z/t) + 24.30(z/t)^2 - 28.68(z/t)^3 + 11.18(z/t)^4]$$

If the heat input is uncertain, an estimate for stainless steel manual metal arc welds can be based on the deposited weld metal cross-section area and the number of passes, see [C.8]. Otherwise the low heat input profiles provide a conservative bound.

C.8 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 surface profiles are the same as those recommended for plate T-butt welds. The profiles for the pipe on pipe geometry are for the stresses in the chord and not the brace member (see Figures C.4(b) and C.4(d)).

The data used to generate the pipe T-butt weld profiles were obtained from geometries where the ratio of the chord thickness to the brace thickness varied from 1.375 to 2. That is, the ratio t/T (see Figures C.4(b) and C.4(d)) varied from 1.375 to 2. For cases 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 geometries varied from 1.5 to approximately 2. The profiles recommended 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 an alternative.

C.8.1 Longitudinal Residual Stresses.

The surface profile for ferritic steel, austenitic steel and aluminium is shown Figure C.4(a). The calculation of the parameters r_0 and y_0 is given in Appendix C.1.

The through thickness variation of longitudinal residual stresses away from the weld centre line is given in Figure C.4(b). This is an upper bound to data 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 welds:

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

C.8.2 Transverse Residual Stresses

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

The through thickness variation of transverse residual stresses away from the weld toe is given in Figure C.4(d). This is an upper bound to data 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 welds since no data from austenitic steel were obtained:

$$\sigma_R^T / \sigma_y^* \, (z/t) = 0.97+2.327(z/t)-24.125(z/t)^2+42.485(z/t)^3-21.087(z/t)^4$$

C.9 Set in Nozzle

The surface residual stress profiles (Figures C.5(a) and C.5(c)) are based on the recommendations of Leggatt [C.7]. The stresses on line A_iA_o are based on the general observation that longitudinal stresses in butt welds can be of weld yield stress magnitude throughout the thickness. This agrees with the Sanderson [C.2] recommendations for cylinder-to-dome welds. The distributions for longitudinal and transverse stresses on line B_iB_o are the same as those recommended for plate T-butt welds. This distribution only applies for defects initiating at or near the toe of the weld.

C.9.1 Longitudinal Residual Stresses

The surface profile for ferritic steel, austenitic steel and aluminium is shown in Figure C.5(a). The calculation of the parameters r_0 and y_0 is given in Appendix C.1.

The through thickness profiles are shown in Figure C.5(b) for the nozzle (Line B_iB_o) and vessel (Line A_iA_o). The calculation of the parameter r_0 is given in Appendix C.1.

C.9.2 Transverse Residual Stresses

There is currently no profile proposed for surface transverse residual stress because there are insufficient data available and it is geometry sensitive. For the interim, a uniform stress σ_R^T equal to the lower of the parent or weld metal yield strength should be considered.

The through thickness profiles are shown in Figure C.5(d) for the nozzle (Line B_iB_o) and Vessel (Line A_iA_o). The distribution of transverse stress on A_iA_o is based on the recommendation in [C.2] for a nozzle-cylinder weld.

C.10 Set on Nozzle

The surface residual stress profiles (Figures C.6(a) and 6(c)) are based on [C.7]. The stresses on line A_iA_o are based on the general observation that longitudinal stresses in butt welds can be of weld yield stress magnitude throughout the thickness. This agrees with the Sanderson [C.2] recommendations for cylinder-to-dome welds. The distributions for longitudinal and transverse stresses on line B_iB_o are the same as those recommended for plate T-butt welds. This distribution only applies for defects initiating at or near the toe of the weld.

C.10.1 Longitudinal Residual Stresses

The surface profile for ferritic steel, austenitic steel and aluminium is shown in Figure C.6(a). The calculation of the parameter y_0 is given in Appendix C.1.

The through thickness profiles are shown in Figure C.6(b) for the nozzle (Line A_iA_o) and vessel (Line B_iB_o). The calculation of the parameter r_0 is given in Appendix C.1.

C.10.2 Transverse Residual Stresses

There is currently no profile proposed for surface transverse residual stress because there are insufficient data available and it is geometry sensitive. For the interim, a uniform stress σ_R^T equal to the lower of the parent or weld metal yield strength should be considered.

The through thickness profiles are shown in Figure C.6(d) for the nozzle (Line A_iA_o) and vessel (Line B_iB_o). The calculation of the parameter r_0 is given in Appendix C.1.

C.11 Repair Welds

Repair welds are usually introduced into structures, either to remedy initial fabrication defects found in castings or welds by routine inspection, or to rectify in-service degradation of components. Residual stresses introduced by deep repair welds tend to dominate any weld residual stresses remaining from an original weld, in the vicinity of the repair. Therefore, the recommended profiles for repair welds that follow can often be used for fracture assessment irrespective of the fabrication history. However, when the significance of the original residual stress field or original weld metal properties is uncertain, a sensitivity fracture assessment should be performed using a residual stress profile for the original weld.

The sizes of repairs can range from being shallow and short, to deep and long, sometimes penetrating the wall or extending along the entire length of an original weld. The repairs can be completely embedded in an original weld, transversely offset from the original weld centre-line, or can transversely span and encompass the entire original weld.

The information presented here is generally applicable to short repair welds. As short repairs tend to induce higher residual stresses than long repairs, the recommended profiles should be bounding for repairs of all lengths. The profiles may be excessively conservative for deep repairs centrally embedded in the original weld and extending the full length of the weld. In this case, the residual stress profile for the original weld is likely to be more appropriate.

The recommended transverse and longitudinal through-thickness residual stress profiles, which are identical to each other, are illustrated in Figures C.7(b) and (d) and can be used for any length of repair.

The surface profile presented in Figure C.7(a) is applicable to short repairs. The surface profile in Figure C.7(c) must be used only for a full length repair.

C.11.1 Longitudinal Residual Stresses

The recommended surface profile for ferritic steel, austenitic steel and aluminium is given in Figure C.7(a). The calculation of the parameters r_0 and y_0 is given in Appendix C.1.

The through thickness profile is given in Figure C.7(b). Over the depth of the repair, z_r, 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. The distance z_0 defines the size of the yield zone below the repair and is related to the heat input of the repair weld root passes.

$\sigma_R^L / \sigma_y^+ (z/t) = 1$ for $z < z_r$

$\sigma_R^L / \sigma_y^+ (z/t) = (z_0+z_r-z)/ z_0$ for $z_r < z < (z_r+z_0)$

$\sigma_R^L / \sigma_y^+ (z/t) = 0$ for $z > (z_r+z_0)$

where z_r = the depth of the repair, mm

$z_0 = r_0$ as defined by Appendix C.1 equation (a), substituting the yield stress, σ_y^* (equal to the lower of the parent or weld metal typical yield strength) for σ_{yp}.

C.11.2 Transverse Residual Stresses

The recommended surface profile for ferritic steel is given in Figure C.7(c). The through thickness profile is given in Figure C.7(d). Over the depth of the repair, z_r, 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. The distance z_0 defines the size of the yield zone below the repair and is related to the heat input of the repair weld root passes.

$\sigma_R^T / \sigma_y^+ (z/t) = 1$ for $z < z_r$

$\sigma_R^T / \sigma_y^+ (z/t) = (z_0+z_r-z)/ z_0$ for $z_r < z < (z_r+z_0)$

$\sigma_R^T / \sigma_y^+ (z/t) = 0$ for $z > (z_r+z_0)$

where z_r = the depth of the repair, mm

$z_0 = r_0$ as defined by Appendix C.1 equation (a), substituting the yield stress, σ_y^* (equal to the lower of the parent or weld metal typical yield strength) for σ_{yp}.

C.12 Transition Welds

Very little information was found concerning residual stresses in transition welds. The only references that were found concerned a pipe butt transition weld and a nozzle to safe end transition weld. The surface profiles shown in Figures C.8(a) and C.8(c) are bounded by the surface profiles of normal pipe butt welds (see Figures C.4(a) and C.4(c)). In considering transition welds of other geometries, it is suggested that the surface profile associated with that particular geometry for austenitics may be used with caution. As for the distributions in Figures C.8(a) and C.8(c), the residual stress in the ferritic material will be zero for all other geometries.

As a further refinement, the longitudinal residual stress in the ferritic parent plate along the austenitic-ferritic fusion boundary might be considered to be zero. Also, the transverse residual stress in the ferritic parent plate might be considered to fall off to zero within one plate thickness from the fusion boundary. Caution should be used with this approach, however, since there are no supporting data.

C.13 Weld T Intersections

The only 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 terminate in order to join or cross the other (continuous) weld. Two treatments are suggested for the assessment of residual stress:

If the terminating weld 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 the relevant geometry (i.e. the effect of the intersection should be ignored).

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 stress magnitude.

C.14 References

[C.1] P A R Mathieson, A compendium of as-welded residual stress profiles, Nuclear Electric Report TD/SIB/MEM/0233 (1991).

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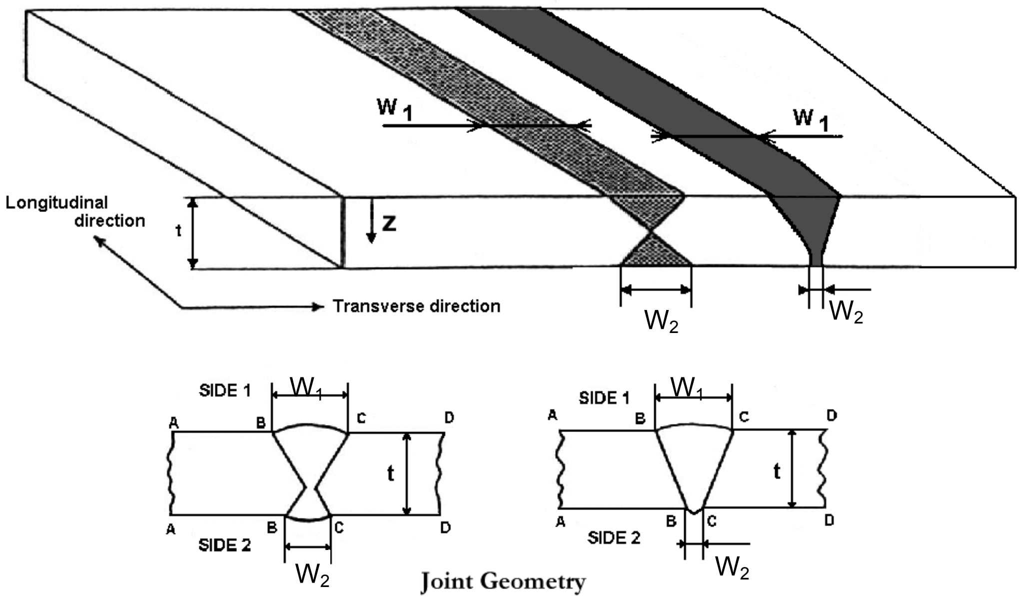
Table C. 1 Validity ranges for as-welded residual stress distributions in ferritic steels

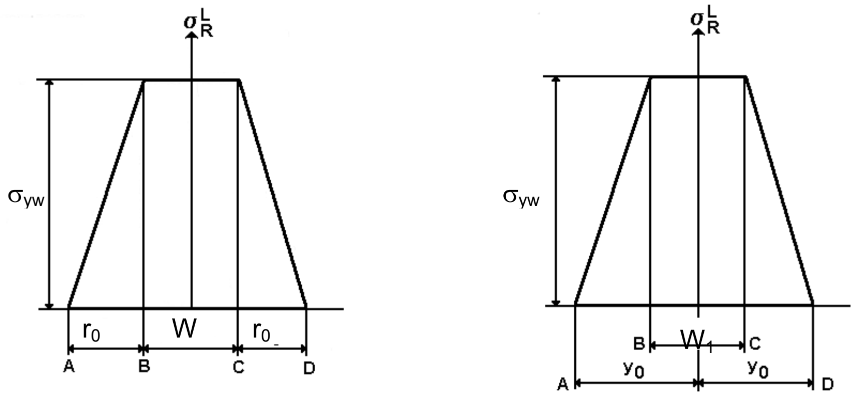
Geometry	Thickness (mm)	Yield Strength (MPa)	Electrical Heat Input per Unit Length (KJ/mm)
Plate Butt Welds	24 - 300	310 - 740	1.6 – 4.9
Pipe Circumferential Butt Welds	9 - 84	225 - 780	0.35 – 1.9
Pipe Seam Welds	50 - 85	345 - 780	Not known
T butt Welds	25 - 100	375 - 420	1.4
Tubular and pipe to plate welds	22 - 50	360 - 490	0.6 – 2.0
Repair Welds	75 - 152	500 - 590	1.2 – 1.6

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

Geometry



(a) Longitudinal Surface Residual Stress. σ_R^L



Side 1: $W = W_1$

Thin material ($r_0 > t$)

Side 2: $W = W_2$

Figure C.1 - Plate butt and pipe seam welds

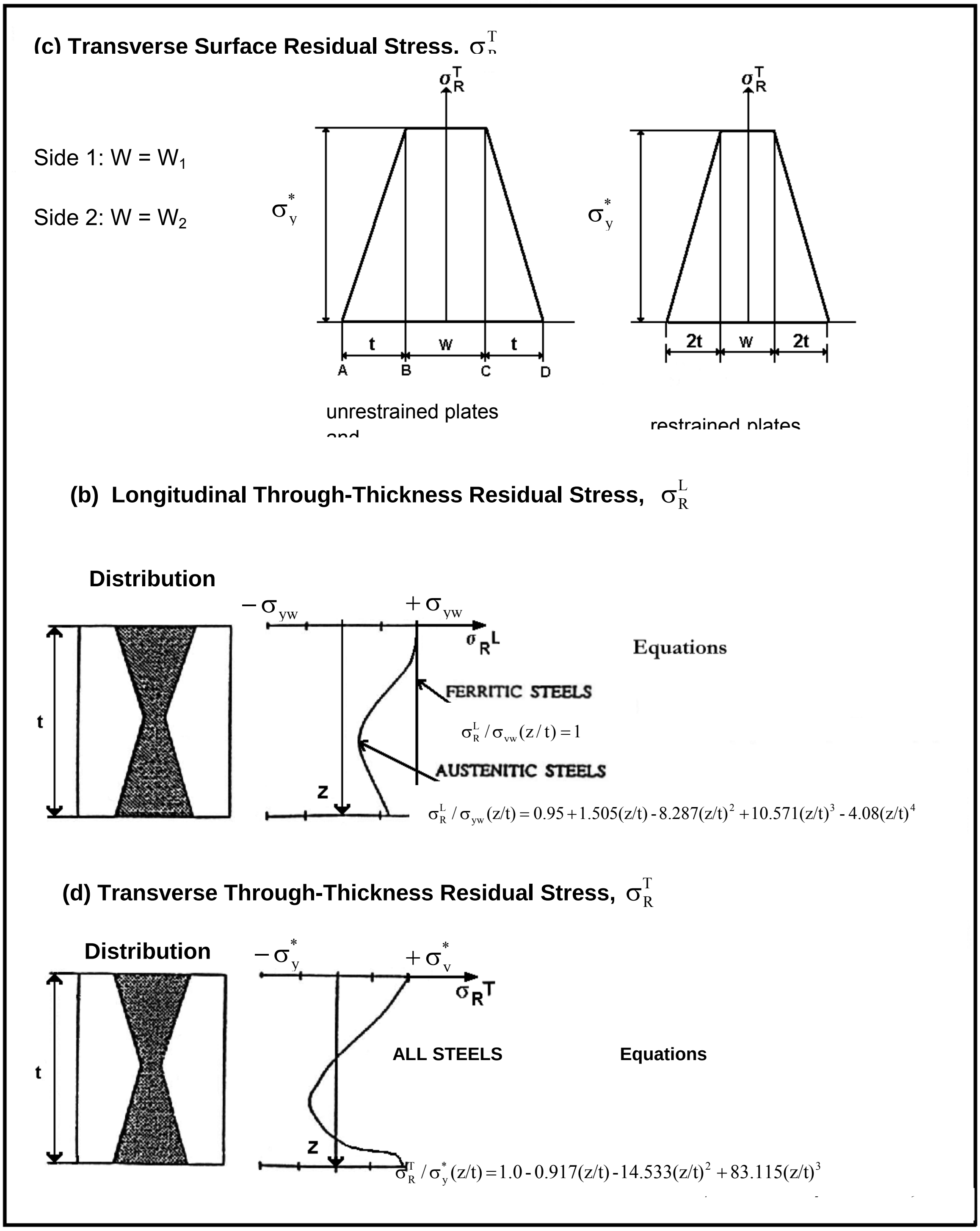
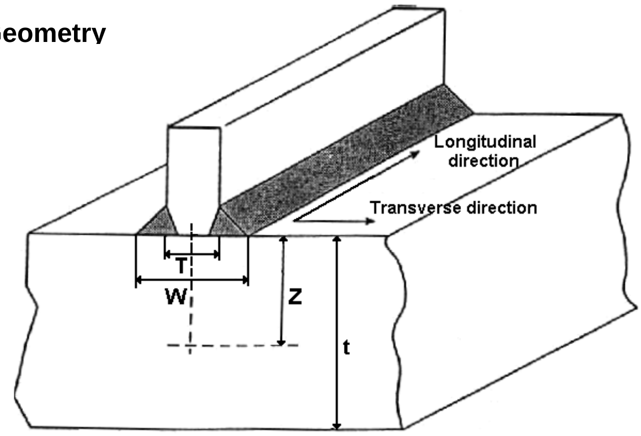
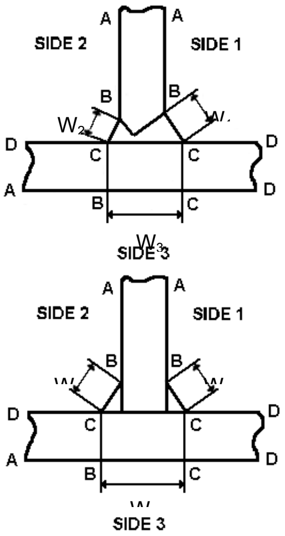


Figure C.1 - (cont)

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

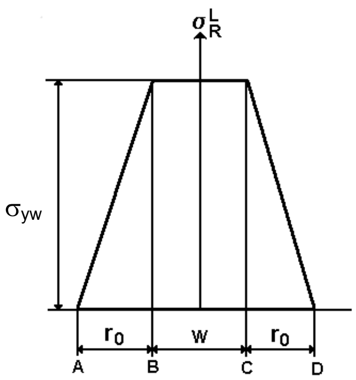
Geometry

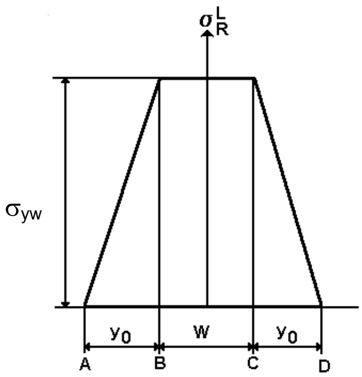




Joint Geometry

(a) Longitudinal Surface Residual Stress, σ_R^L





Side 1: $W = W_1$

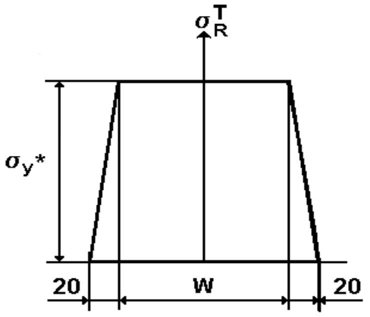
Side 2: $W = W_2$

Side 1: $W = W_1$, $\sigma_y = \sigma_{yw}$

Side 2: $W = W_2$, $\sigma_y = \sigma_{yw}$

Figure C.2 - Plate T-butt welds

(c) Transverse Surface Residual Stress, σ_R^T



(b) Longitudinal Through-Thickness Residual Stress, σ_R^L

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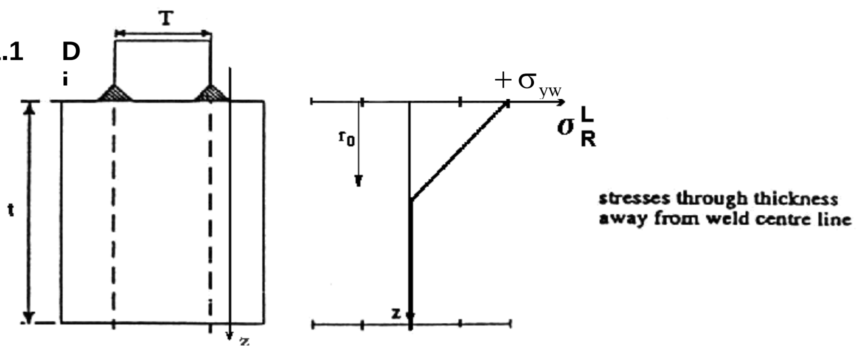
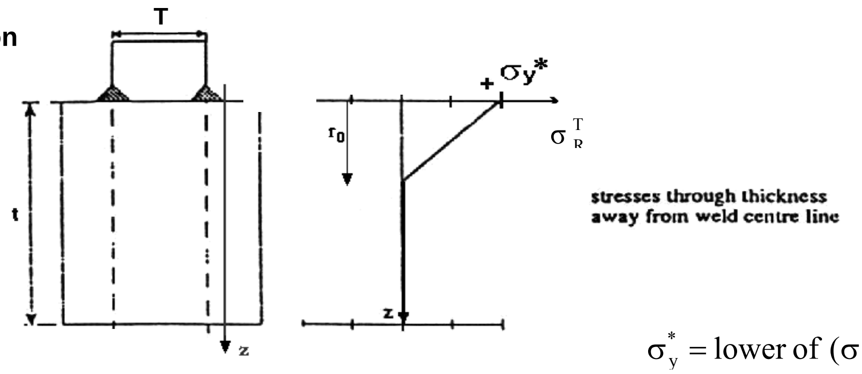


(d) Transverse Through-Thickness Residual Stress, σ_R^T

Distribution



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

Figure C.2 - (cont)

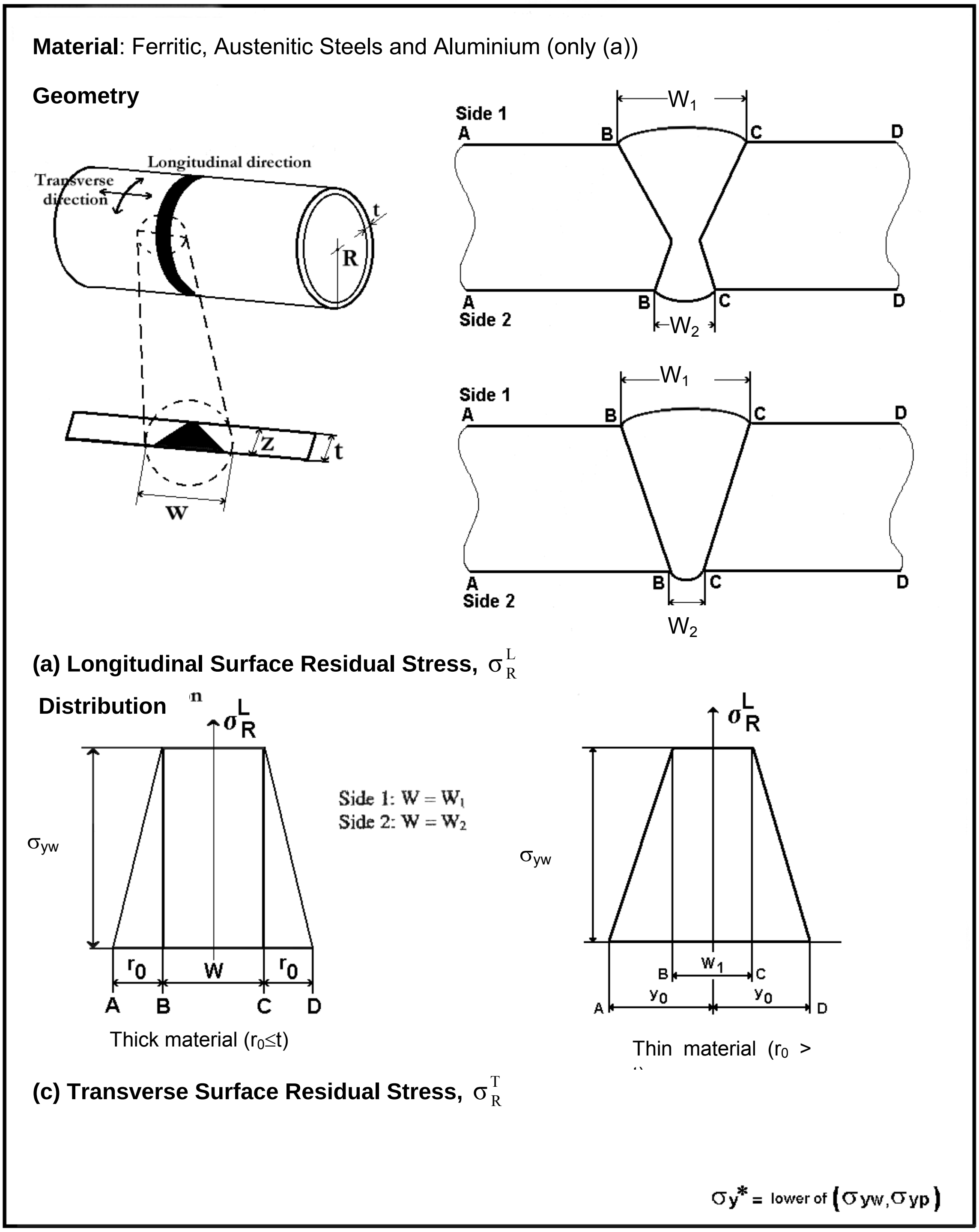
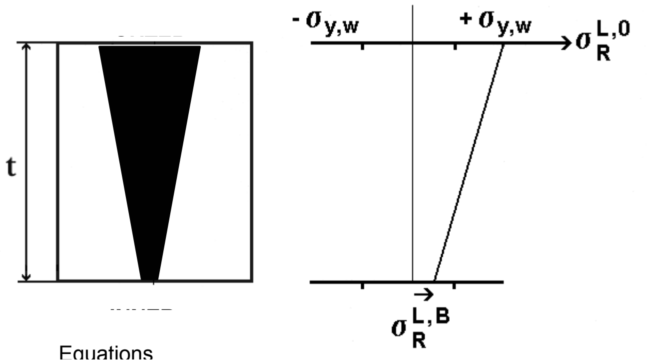


Figure C 3 - Pipe butt welds

(b) Longitudinal Through-Thickness Residual Stress, σ_R^L



Equations

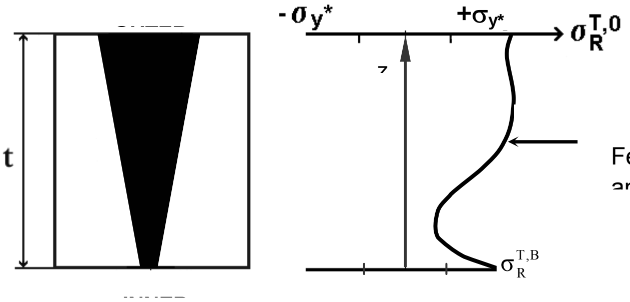
$\sigma_R^{L,0} = \sigma_{yw}$

$\sigma_R^{L,B} = A_b \sigma_{yw}$ where : $A_b = 1$ $\quad 0 < t \le 15\,mm$

$A_b = 1 - 0.0143\ (t - 15)$ $\quad 15\,mm < t \le 85\,mm$

$A_b = 0$ $\quad t > 85\,mm$

(d) Transverse Through-Thickness Residual Stress, σ_R^T



Ferritic steel low heat input, and

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

Distribution Equations

For high heat input ferritic and austenitic welds where [(q/v)/t]>120 J/mm^2

$$\sigma_R^T = \sigma_y^*[1.00 - 0.22(z/t) - 3.06(z/t)^2 + 1.88(z/t)^3]$$

For medium heat input ferritic welds where 50 J/mm^2<[(q/v)/t]≤ 120 J/mm^2

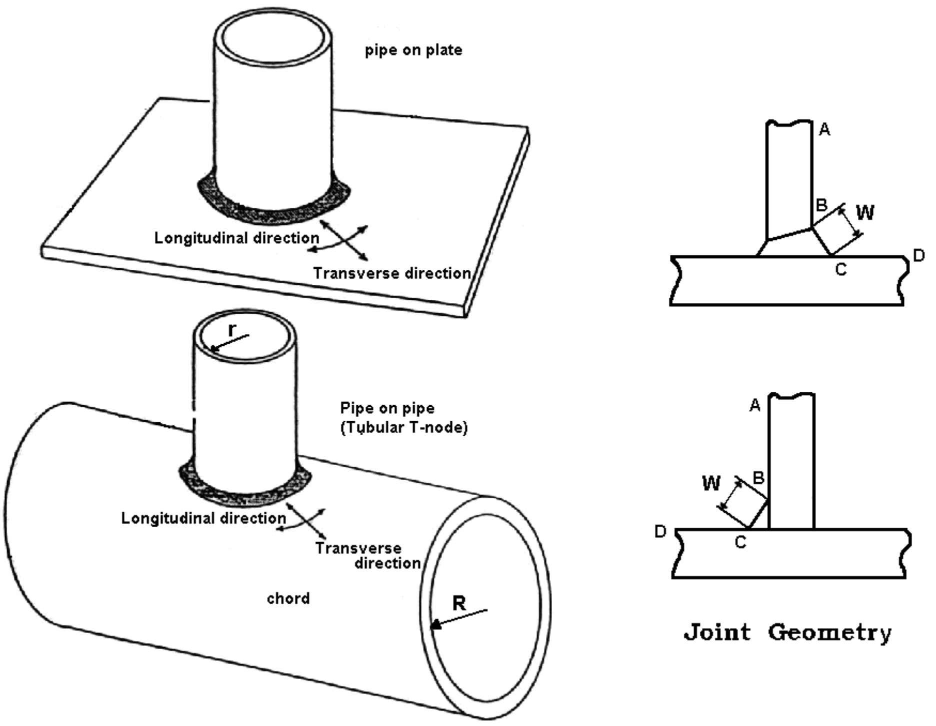
$$\sigma_R^T = \sigma_y^*[1.00 - 4.43(z/t) + 13.53(z/t)^2 - 16.93(z/t)^3 + 7.03(z/t)^4]$$

For low heat input ferritic welds where [(q/v)/t]≤ 50 J/mm^2, and for medium/low heat input austenitic

welds where [(q/v)/t]≤ 120 J/mm^2

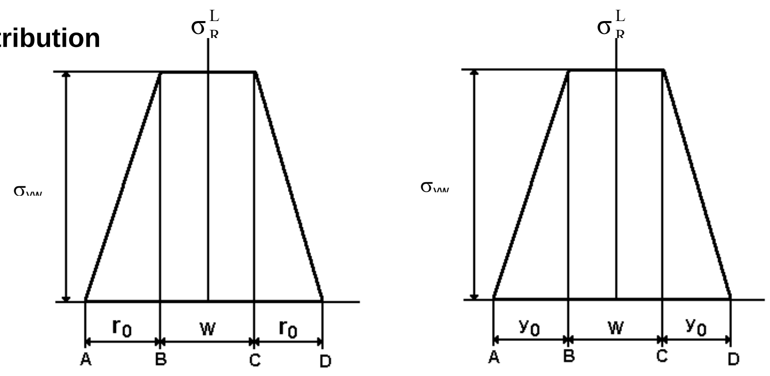
Figure C.3 - (cont)

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



(a) Longitudinal Surface Residual Stress, σ_R^L

Distribution

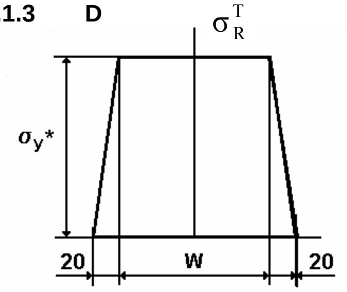


Thick material ($r_0 \leq t$)   Thin material ($r_0 > t$)

Figure C.4 - Pipe-T-butt welds

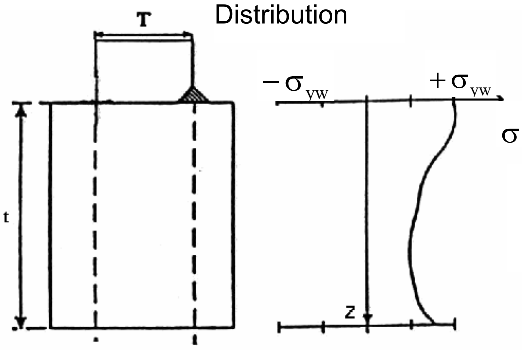
(c) Transverse Surface Residual Stress, σ_R^T

C..1.1.1.3 D



(b) Longitudinal Through-Thickness Residual Stress, σ_R^L

Distribution

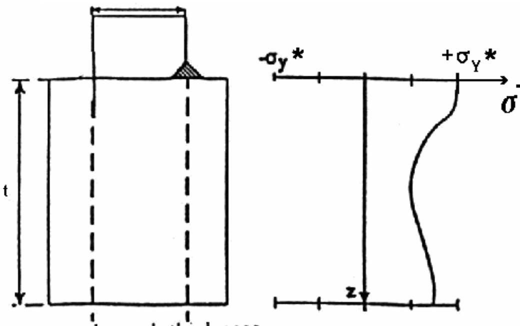


Equations

FERRITIC STEELS

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

(d) Transverse Through-Thickness Residual Stress, σ_R^T



Equations

FERRITIC STEELS

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

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

Figure C.4 - (cont)

Material: Ferritic, Austenitic Steels and Aluminium

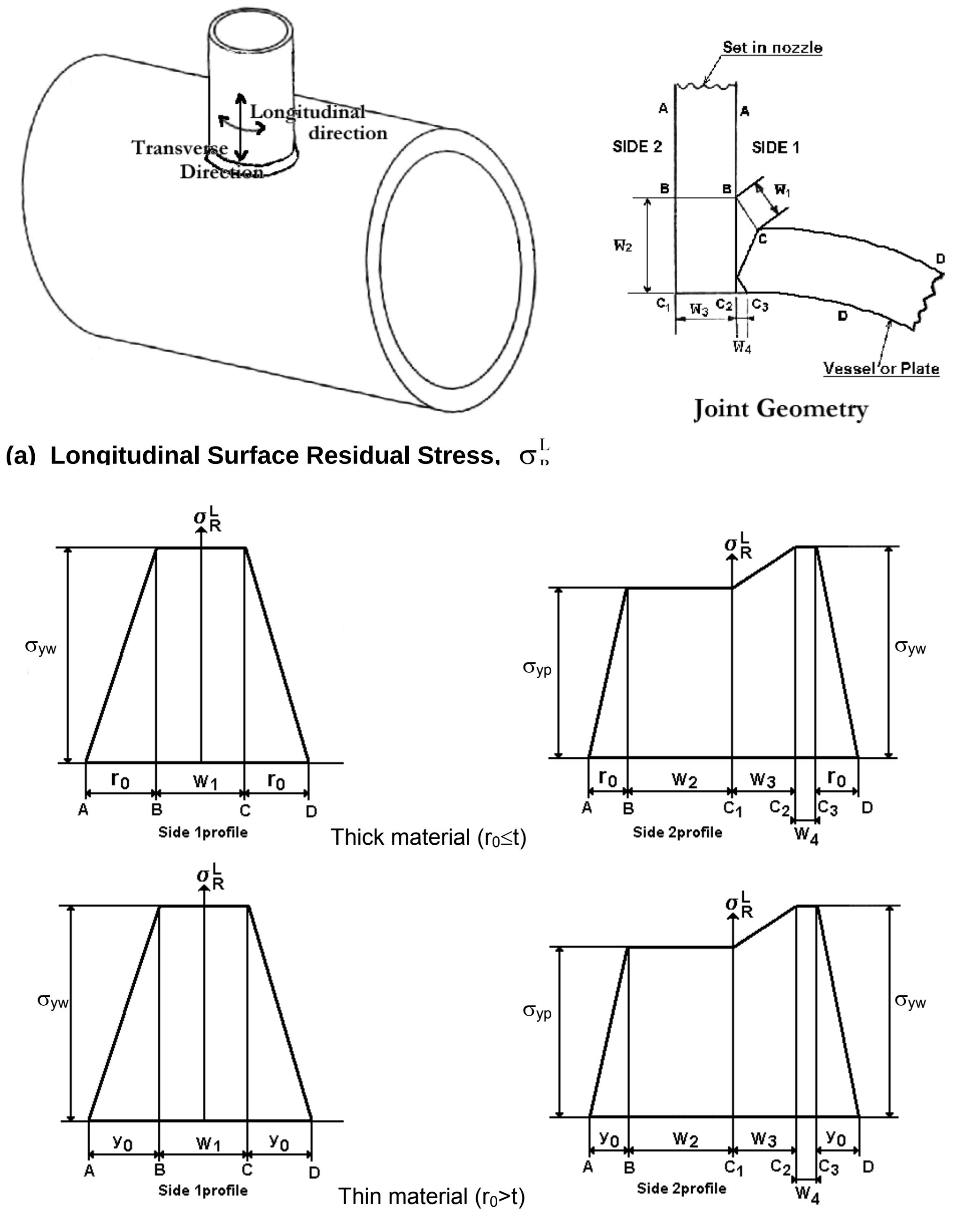
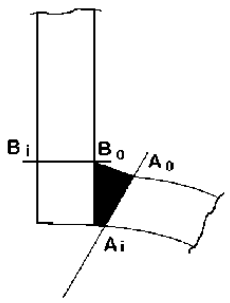


Figure C.5 - Set-in nozzle

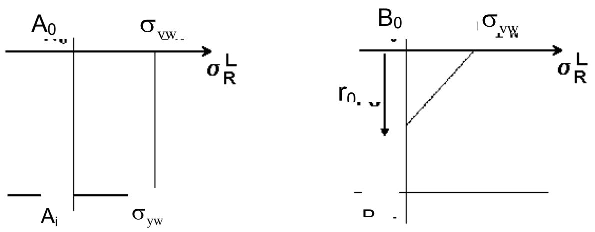
(c) Transverse Surface Residual Stress σ_R^T

Use uniform $\sigma_R^T = \sigma_y^*$

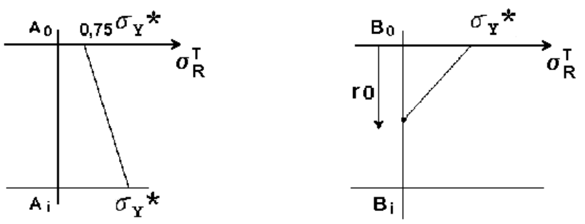


(b) Longitudinal Through-Thickness Residual Stress, σ_R^L

Distribution



(d) Transverse Through-Thickness Residual Stress, σ_R^T Distribution

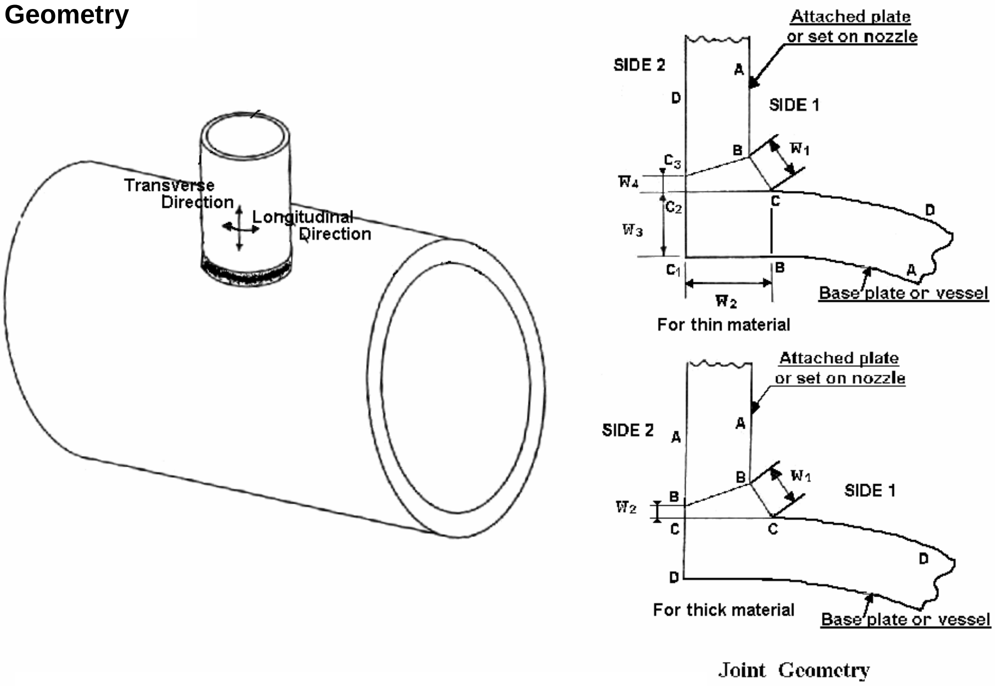


$\sigma_y^* =$ lower of $(\sigma_{yw}, \sigma_{yp})$

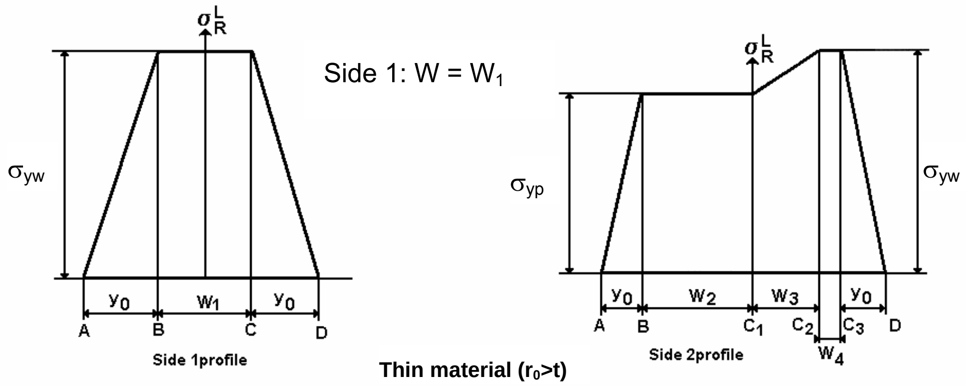
Figure C.5 - (cont)

Material: Ferritic, Austenitic Steels and Aluminium

Geometry



(a) Longitudinal Surface Residual Stress, σ_R^L Distribution



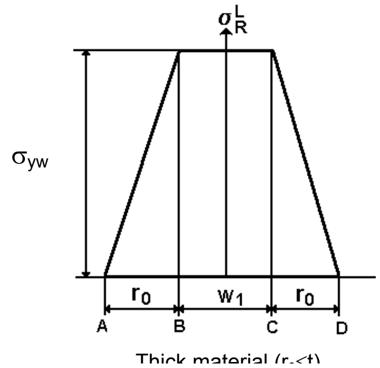
Thin material (r_0>t)

Figure C.6 - Set-on nozzle

Distribution

Side 1: $W = W_1$

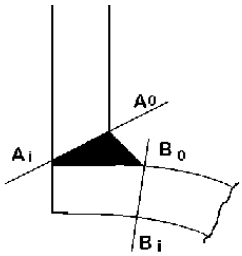
Side 2: $W = W_2$



(c) Transverse Surface Residual Stress σ_R^T

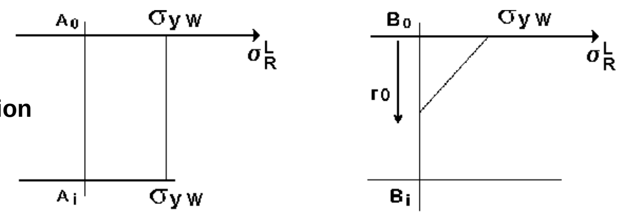
Use uniform $\sigma_R^T = \sigma_y^*$

Through-Thickness Profiles



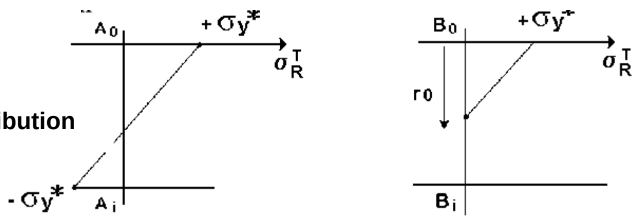
(b) Longitudinal Through-Thickness Residual Stress σ_R^L

Distribution



(d) Transverse Through-Thickness Residual Stress, σ_R^T

Distribution



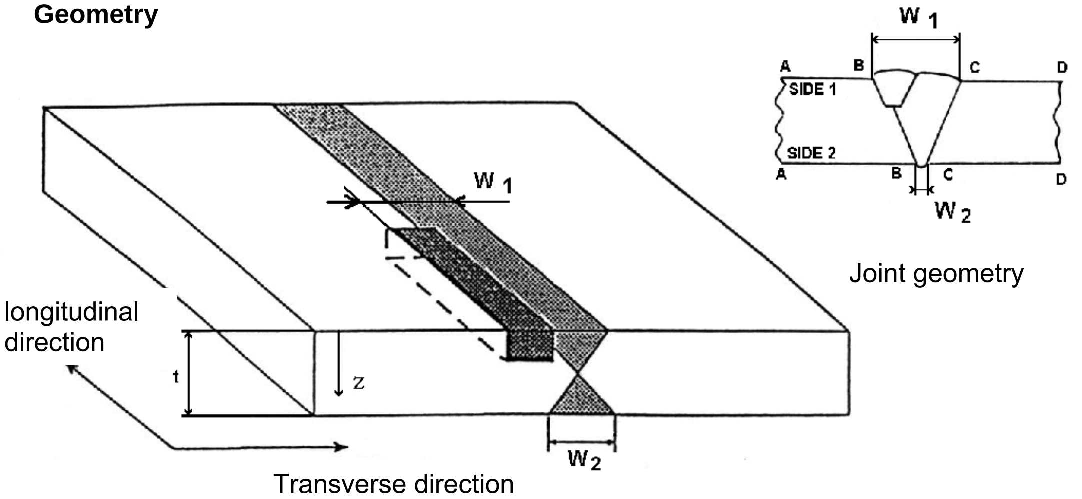
σ_y^* = lower of $(\sigma_{yw}, \sigma_{yp})$

Figure C.6 - (cont)

Material: Ferritic, Austenitic Steels and Aluminium (a)

Ferritic Steels (b), (c), (d)

Geometry



(a) Longitudinal Surface Residual Stress, σ_R^L

Distribution

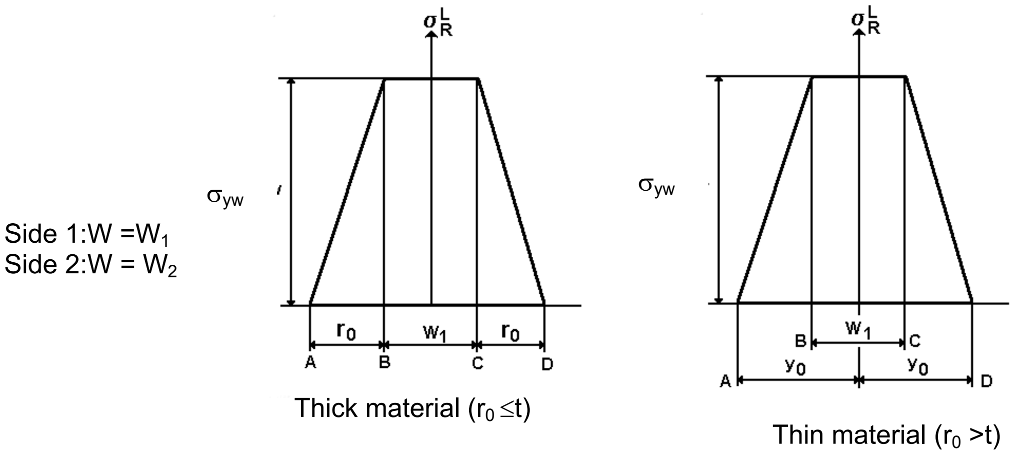
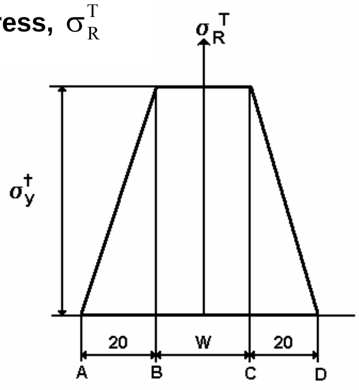


Figure C. 7 - Repair welds

(c) Transverse Surface Residual Stress, σ_R^T

Distribution

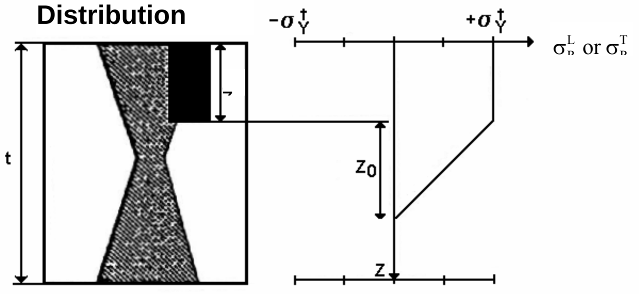
Side 1 : W = W_1



(b) Longitudinal Through-Thickness Residual Stress, σ_R^L and

(d) Transverse Through-Thickness Residual Stress σ_R^T

Distribution



Distribution Equations (Longitudinal and Transverse Stresses)

$\sigma_R^L / \sigma_y^+ (z/t) = \sigma_R^T / \sigma_y^+ (z/t) = 1$ for $z < z_r$

$\sigma_R^L / \sigma_y^+ (z/t) = \sigma_R^T / \sigma_y^+ (z/t) = (z_0+z_r-z)/ z_0$ for $z_r < z < (z_r+z_0)$

$\sigma_R^L / \sigma_y^+ (z/t) = \sigma_R^T / \sigma_y^+ (z/t) = 0$ for $z > (z_r+z_0)$

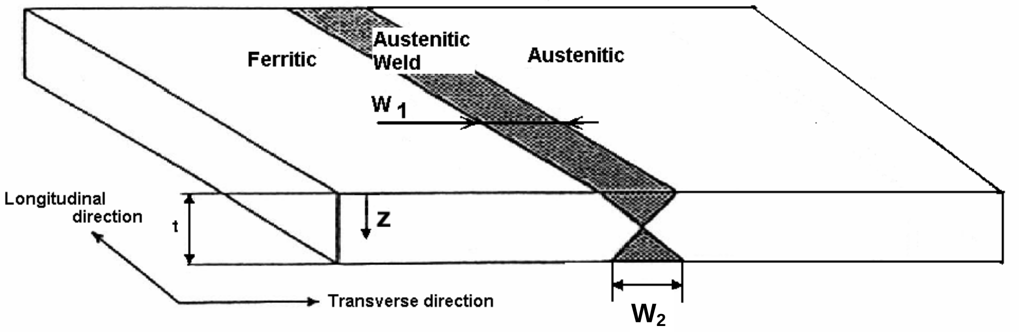
σ_y^+ = greater of (parent, weld or repair weld yield stress)

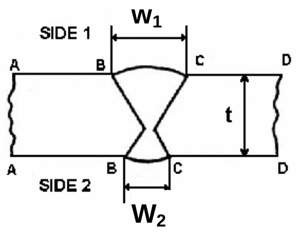
z_r = the depth of the repair, mm

$z_0 = r_0$ as defined by Appendix IV.4.1 equation (a), substituting the yield stress, σ_y* (equal to the lower of the parent or weld metal typical yield strength) for σ_{yp}.

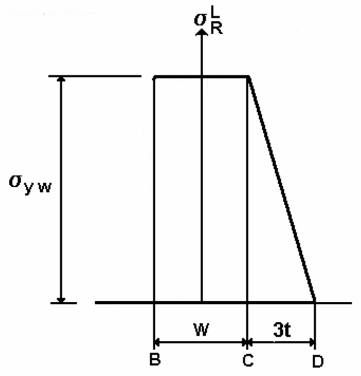
Figure C.7 - (cont)

Geometry





(a) Longitudinal Surface Residual Stress, σ_R^L

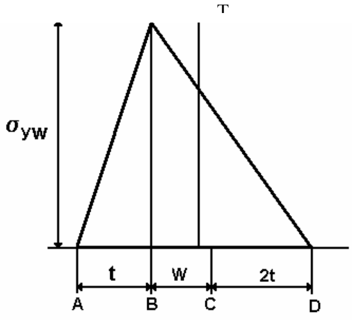


Side 1: $W = W_1$
Side 2: $W = W_2$

Figure C.8 - Transition welds

(c) Transverse Surface Residual Stress, σ_R^T

Side 1 : W = W_1



(b, d) Through-Thickness Residual Stress Profiles

**NO INFORMATION:
SEE SECTION C.12**

Figure C.8 - (cont)

Appendix C.1 Calculation of the Dimensions of the Yielded Zone

The calculations of the parameters, r_0 and y_0, which define the size of the yield zone at the weld, are based on the recommendations of Leggatt [C.7] for surface residual stress profiles.

If $r_0 \leq t$, where t is the plate thickness (mm):

$$r_0 = \sqrt{\frac{K}{\sigma_{yp}} . \frac{\eta q}{\nu}} \qquad \text{(a)}$$

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/mm^2

q = arc power = IV, J/sec

I = current, A

V = voltage, V

ν = weld travel speed, mm/sec

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

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.

If $r_0 > t$

$$y_0 = \frac{1.033K}{\sigma_{yp}} . \frac{\eta q}{\nu t} \qquad \text{(b)}$$

In a butt weld, t is the plate thickness (mm). 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 + 0.5t_a). In a corner joint with the same definitions of t_a, t is taken as 0.5(t_a + t_b).

Equation (b) applies if y_0 > 1.033 t. If y_0 < 1.033t, equation (a) is used. In general, equation (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:

$$K=2\alpha E/(e\pi\rho c) \quad \text{(c)}$$

where;

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

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

e = 2.718

ρ = density, kg/mm^3

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

The material properties are taken at ambient temperature ($20^{\circ}C$). Typical values of the relevant properties are listed in Table C.1. Taking a typical value of process efficiency, η= 0.8, gives the following values of $K\eta$:

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

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

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

Table C. 2 Typical material properties

Property	Ferritic Steels	Austenitic Stainless Steels	Aluminium Alloys
coefficient of thermal expansion, α, $^{o}C^{-1}$	12×10^{-6}	16×10^{-6}	24×10^{-6}
Young's modulus, E, N/mm^2	207 000	193000	70 000
Volumetric specific heat, ρc, $Jmm^3/^{o}C$	0.0038	0.0036	0.0024
$K=2\alpha E/(e\pi\rho c)$, Nmm/J	153	201	164

Appendix C.2 More Realistic Level 3 Weld Residual Stress Profiles for Austenitic Stainless Steel Pipe Butt Welds

This appendix defines validated Level 3 (more realistic) through-wall transverse and longitudinal residual stress profiles for butt welds in unrestrained austenitic stainless steel pipes [C.8]. The formulations capture the underlying through-wall weld residual stress distribution and therefore can be used in fracture assessments for structurally significant defects. Moreover, the approximations can be decomposed into membrane, bending and self-equilibrated components to aid stress classification [C.8].

The formulations take account of the arc-welding process by using the net heat input per unit thickness per unit run length to the workpiece, $\tilde{Q}$, as the controlling parameter, defined by:

$$\tilde{Q} = \eta[(q/v)/t]$$

where η = weld process efficiency

q = weld torch arc power (current x closed circuit voltage) J/sec

v = weld torch advance rate, mm/sec

t = pipe thickness, mm

Typical values of weld process efficiency are η = 0.8 for manual metal arc weld and η = 1.0 for submerged arc weld, see European Standard EN 1011-1:1998 [C.9]. If the weld torch arc power is unknown, an estimate for manual metal arc welds can be based on the deposited weld metal cross-section area and the number of passes, see [C.8].

The Level 3 formulations are validated for non-stress relieved girth welds having the following characteristics: over-matched weld material tensile properties, a pipe wall thickness in the range 16mm to 110mm and R/t between 1.8 and 25, single 'J', narrow gap or double 'V' preparations (with external 'V' heat input dominance), manual metal arc, submerged arc and tungsten inert gas weld processes, and electrical heat inputs, (q/v), in the range 1.0 to 2.4 KJ/mm.

The recommended Level 3 profiles do not always capture very localised stress variations (short-range, high-order self-equilibrated stresses), that often arise from weld bead deposition lay-up effects or geometric singularities at the weld root and weld toe. These are not expected to influence fracture from structurally significant defects, that is those having a through-wall dimension greater than the characteristic wavelength of any local stress perturbation of potential concern. They are also unlikely to lead to failure arising from any defects that advance by ductile fracture mechanisms. However, high magnitude tensile near-surface stress fluctuations may significantly influence fracture assessments of shallow defects (<0.1t through-wall extent) or surface points of surface-breaking defects, where stable ductile tearing cannot be claimed or where the material fails by a brittle fracture mechanism such as cleavage. They will also affect integrity assessments of fatigue crack initiation and short crack growth. For these cases, the profiles can be modified by setting the surface stresses equal to the appropriate material yield stress (1% proof stress) and linearly reducing the stress to the formulation value at a depth of 0.1t below the surface [C.8]. This approach has the advantage that the surface values of the through-wall stress distribution match the surface residual stress profiles recommended in Section C.7. The disadvantage is that modified axial stress profiles are no longer in axial force equilibrium and therefore cannot be readily de-convoluted into membrane, bending and self-equilibrating components. The profiles will also be less smooth for some cases, making it more difficult to use weight function methods for stress intensity factor determination. Shallow defects may be influenced by constraint and statistical crack size effects, see Sections II.2 and III.7, which will act to increase the fracture toughness. These features of the material response may be used in assessments to mitigate the impact of very localised residual stresses on shallow defects.

Longitudinal Residual Stress

$$\sigma_R^L\left(\frac{z}{t}\right)=\sigma_{yw}\left\{(0.65-\delta)\sin\left[\frac{3\pi}{2}\left(\frac{7}{6}-\frac{z}{t}\right)\right]+(0.35+\delta)\right\}$$

where $\frac{z}{t}$ = fractional distance through thickness from bore of pipe

$$\delta=4.79\text{x}10^{-3}\tilde{Q}$$

valid for 10 J/mm^2 < $\tilde{Q}$ < 136 J/mm^2

Transverse Residual Stress

$$\sigma_R^T\left(\frac{z}{t}\right)=\sigma_{yp}\left\{\varphi\left(1-2\frac{z}{t}\right)+\theta\sin\left[\frac{\pi}{4}\left(1-8\frac{z}{t}\right)\right]-\frac{t}{R}\left[\frac{\sqrt{2}}{4\pi}\theta-\frac{\varphi}{6}\right]\right\}$$

where $\frac{z}{t}$ = fractional distance through-thickness from bore of pipe,

$$\theta=\tilde{Q}(-1.25\text{x}10^{-8}\tilde{Q}^3+5.42\text{x}10^{-6}\tilde{Q}^2-8.67\times10^{-4}\tilde{Q}+5.11\times10^{-2})$$

$$\varphi=8.4\times10^{-3}\tilde{Q}-0.34$$

for 10 J/mm^2 < $\tilde{Q}$ < 160 J/mm^2

Appendix C.3 Bibliography

Plate Butt Welds

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C.15 Additional Information

This section provides additional information on the residual stress profiles of laser beam (LBW) and friction stir welded (FSW) Al-alloys and laser beam welded steel plates. This informative section aims to provide recent information on the residual stress distributions obtained for thin-walled Al-alloy plates and 25 mm thick steel plates.

C.15.1 Residual Stresses in Laser and Friction Stir Welded Al-Alloy Plates

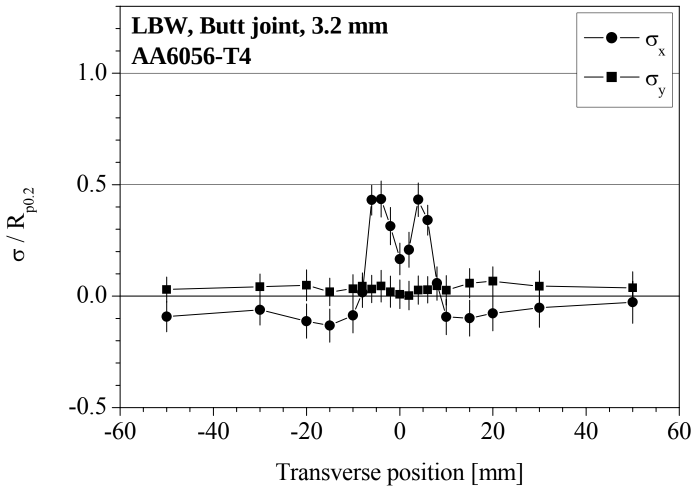

Figure C. 9 – The residual stress distributions across butt-joint of LBW from Al-alloy 6056-T4 (As-welded), 3.2 mm thick (*Ref. P. Staron, W.V. Vaidya, M. Kocak, GKSS, IDA Project, 2005*)

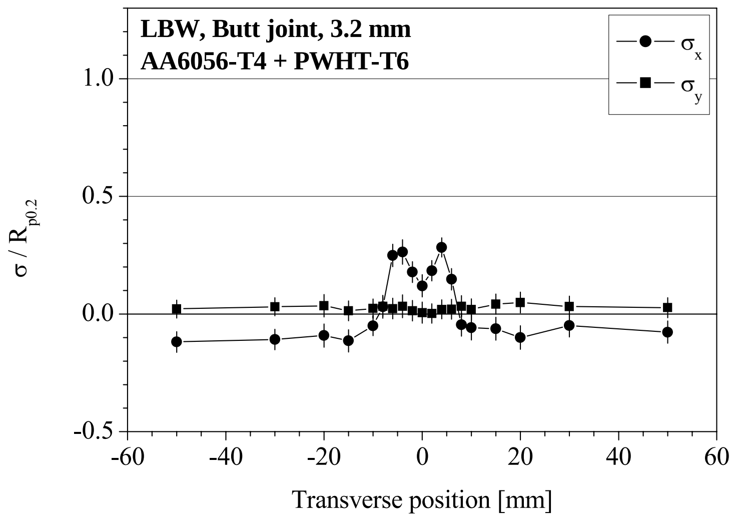

Figure C. 10 – The residual stress distributions across butt-joint of LBW from Al-alloy 6056-T6 (after PWHT of Fig.C17 weld to T6 condition), 3.6 mm thick (*Ref. P. Staron, W.V. Vaidya, M. Kocak, GKSS, IDA Project, 2005*)

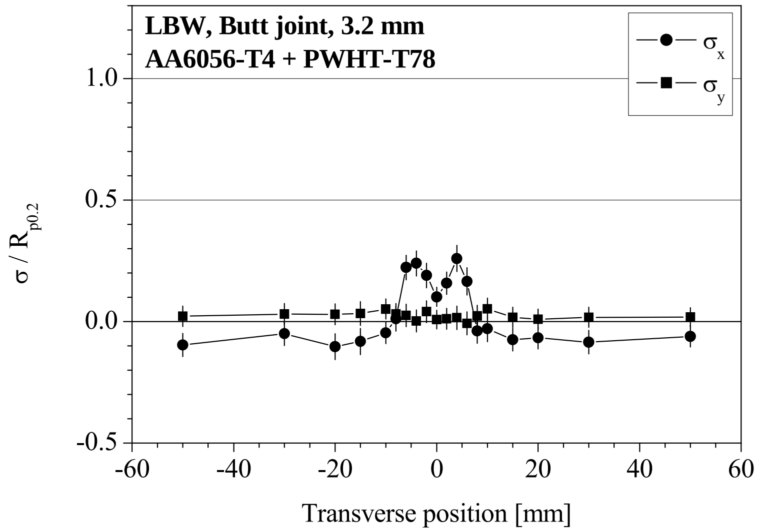

Figure C. 11 – The residual stress distributions across butt-joint of LBW from Al-alloy 6056-T78 (after PWHT of Fig.C17 weld to T78 condition), 3.6 mm thick (*Ref. P. Staron, W.V. Vaidya, M. Kocak, GKSS, IDA Project, 2005*)

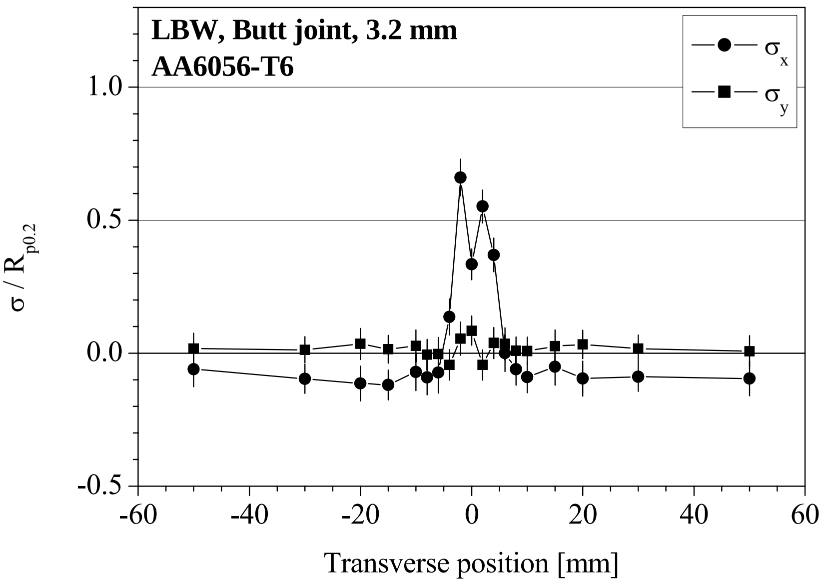

Figure C. 12 – The residual stress distributions across butt-joint of LBW from Al-alloy 6056-T6 (As-welded), 3.2 mm thick (*Ref. P. Staron, W.V. Vaidya, M. Kocak, GKSS, 2005*)

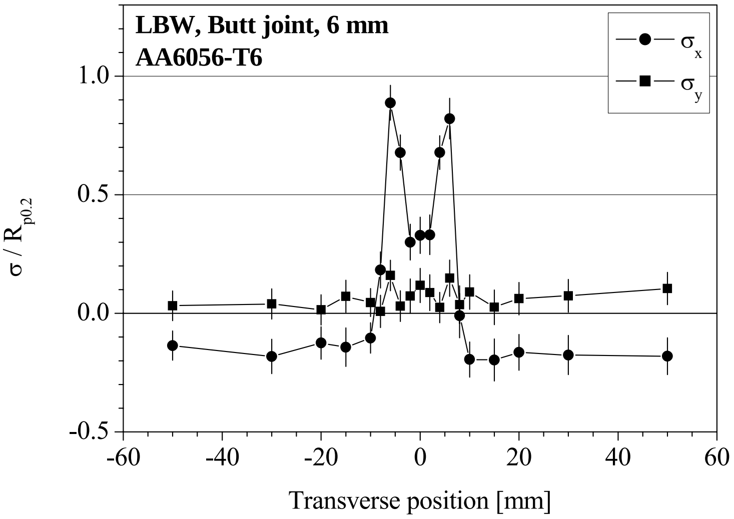

Figure C. 13 – The residual stress distributions across butt-joint of LBW from Al-alloy 6056-T6 (As-welded), 6.0 mm thick (*Ref. P. Staron, W.V. Vaidya, M. Kocak, GKSS, 2005*)

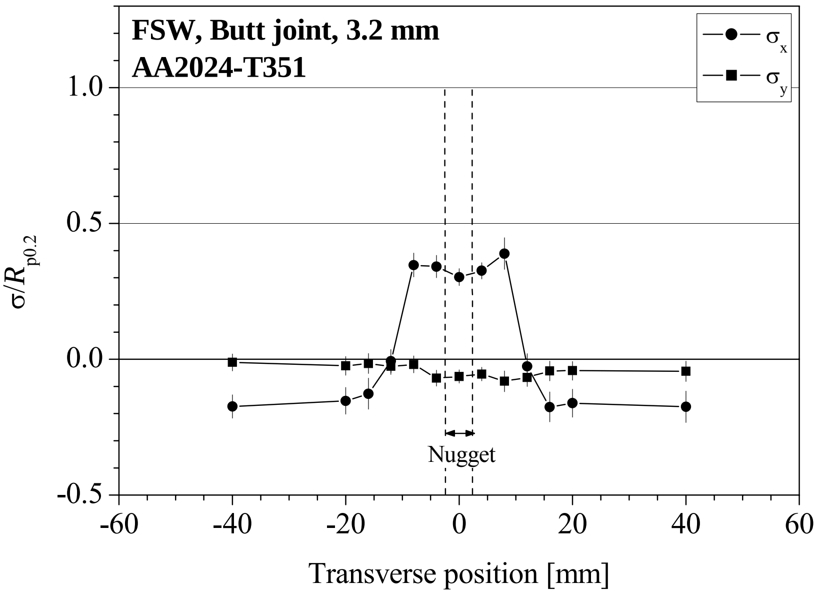

Figure C. 14 – The residual stresses across a 3.2 mm thick FSW butt-joint of Al-alloy 2024-T351, where σ_x = longitudinal stress and σ_y = transverse stress.(*Ref. P. Staron, M. Kocak, GKSS, 2005*).

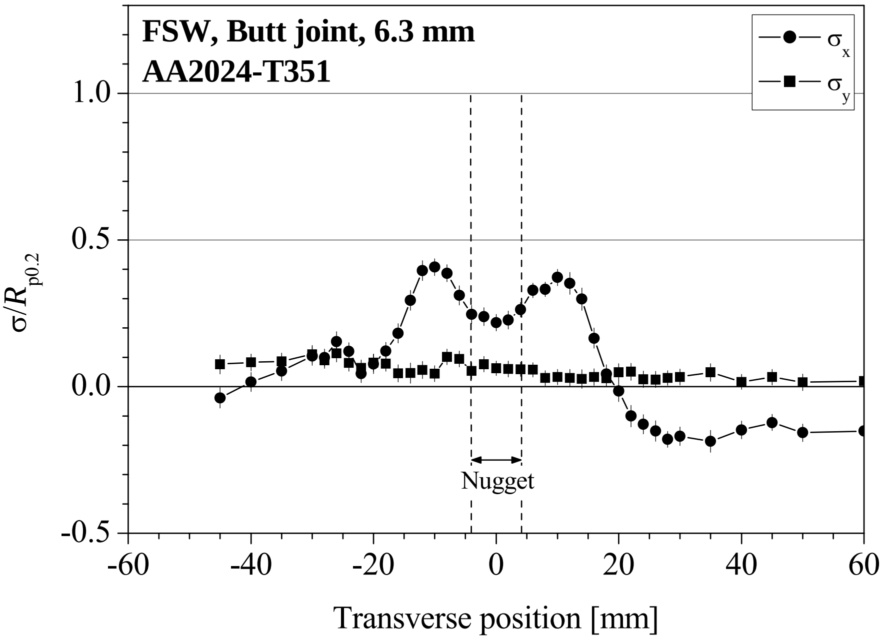

Figure C. 15 – The residual stress distributions across butt-joint of FSW from Al-alloy 2024-T351, 6.3mm thick, where σx = longitudinal stress and σy = transverse stress (*Ref. S. Williams, BAE Systems, UK, P. Staron, M. Kocak, GKSS, 2004*)

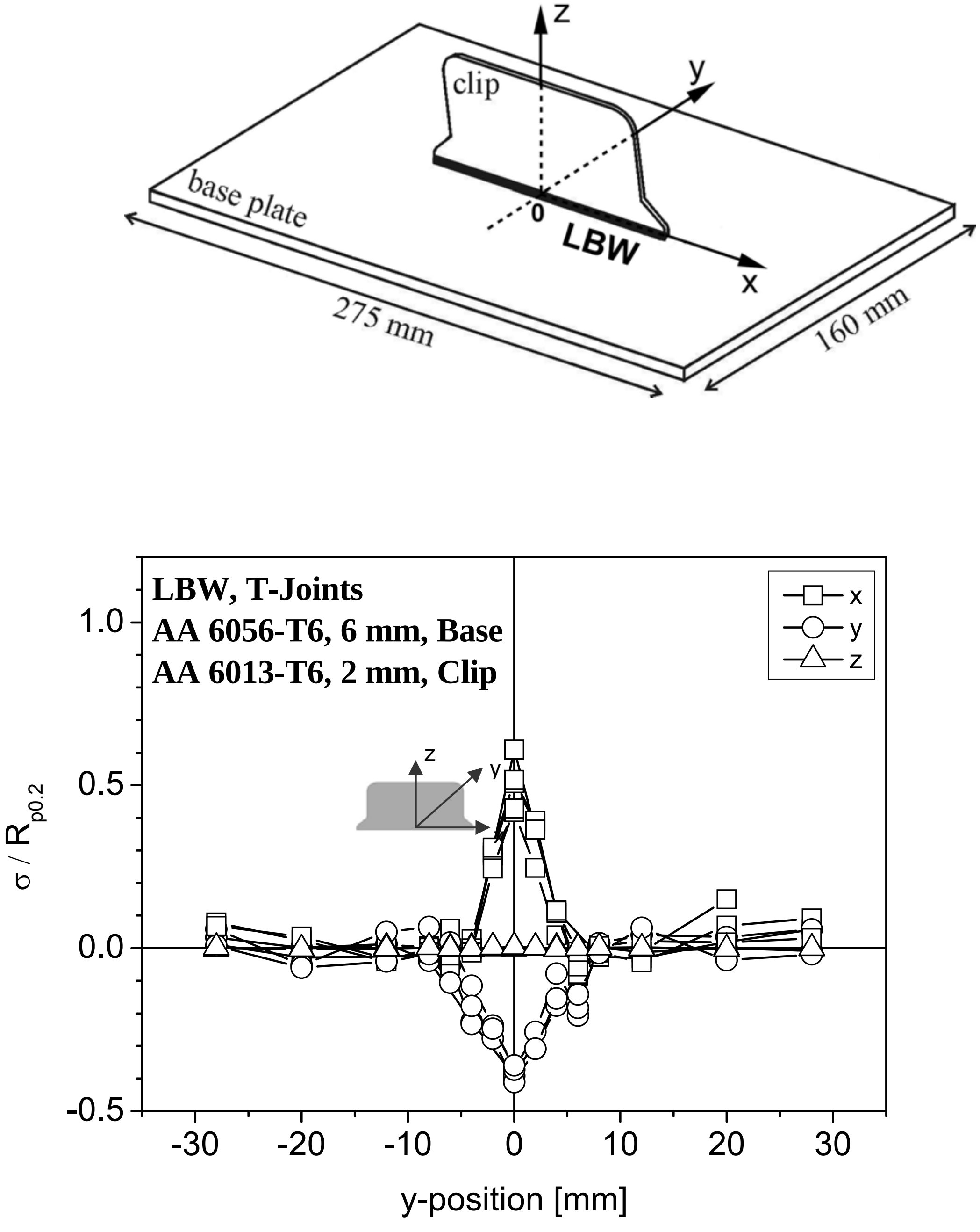

Figure C. 16 – The residual stress distributions across short distance T-joint of LBW from Al-alloy 6056-T6, 6.0 mm thick base metal and 2.0 mm clip part (*Ref. F.S. Bayraktar, P. Staron, M. Kocak, A. Schreyer, GKSS, 2006*)

C.15.2 Laser Welded Steel Plates

This part contains data and charts relating to the distribution of residual stresses in laser-welded steel plates. The data presented here were originally provided by Shuwen Wen (Corus RD&T, Swinden Technology Centre) in 2003 in a paper "Residual Stress in Laser Welds: Measurement and Modelling", which described the predictions from 2D generalised plane-strain finite element models of single-pass and two-pass laser butt welds in 25 mm steel plate typical of products supplied to EN10025 grade S355. The data have been re-presented here in terms of absolute stress values and also in terms of the ratios between stresses and the parent metal yield strength.

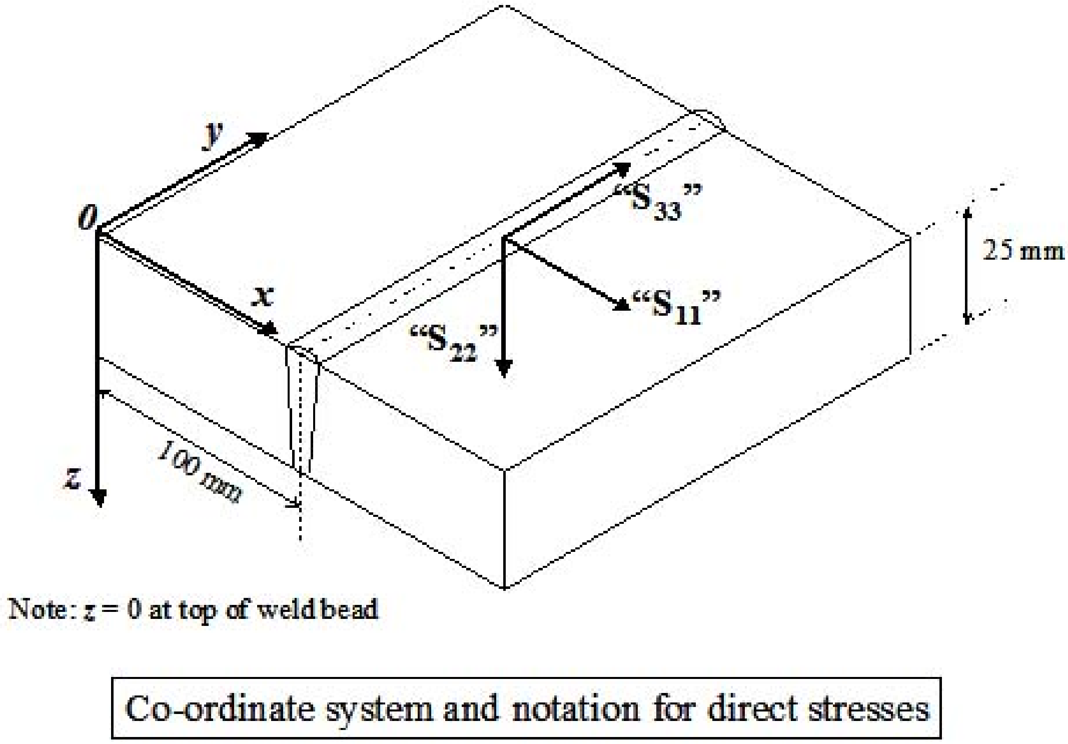

Figure C. 17 – Co-ordinate systems (image)

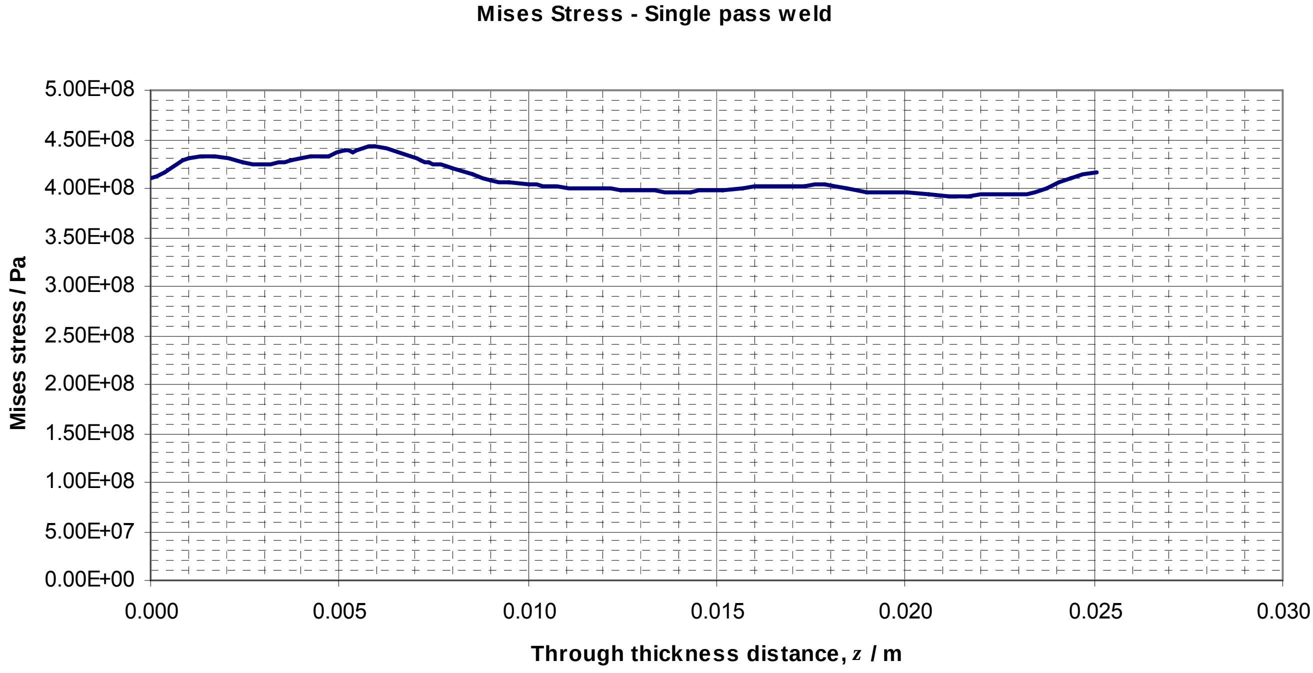

Figure C. 18

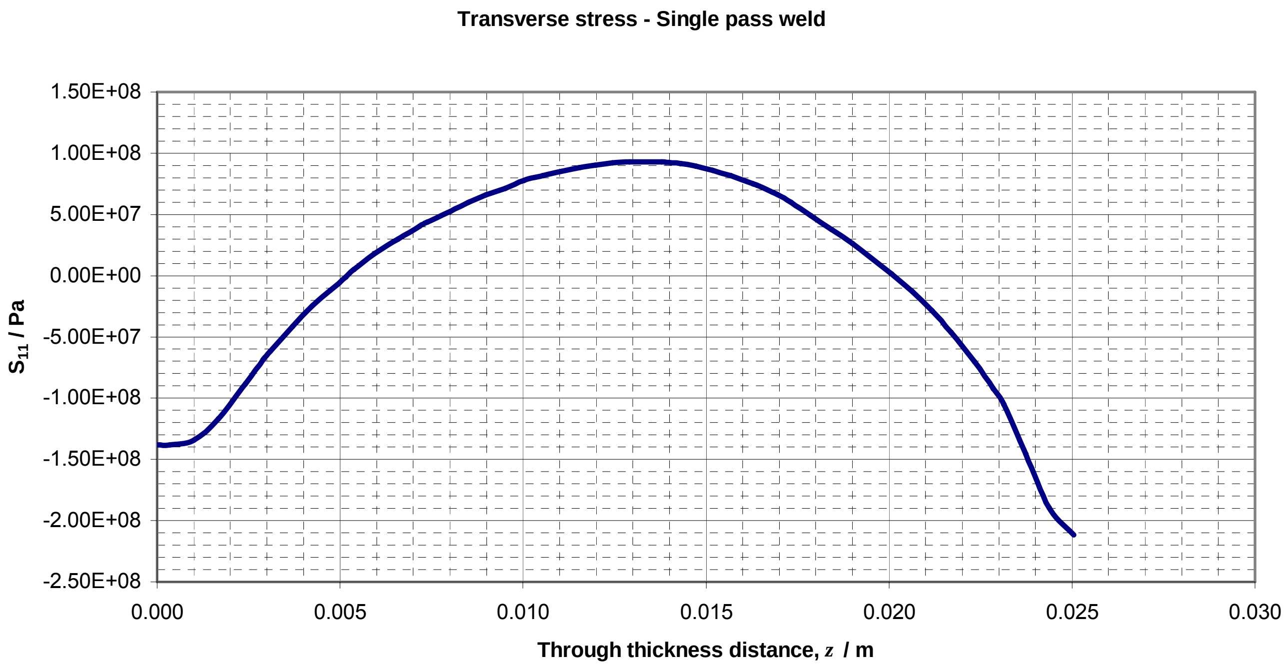

Figure C. 19

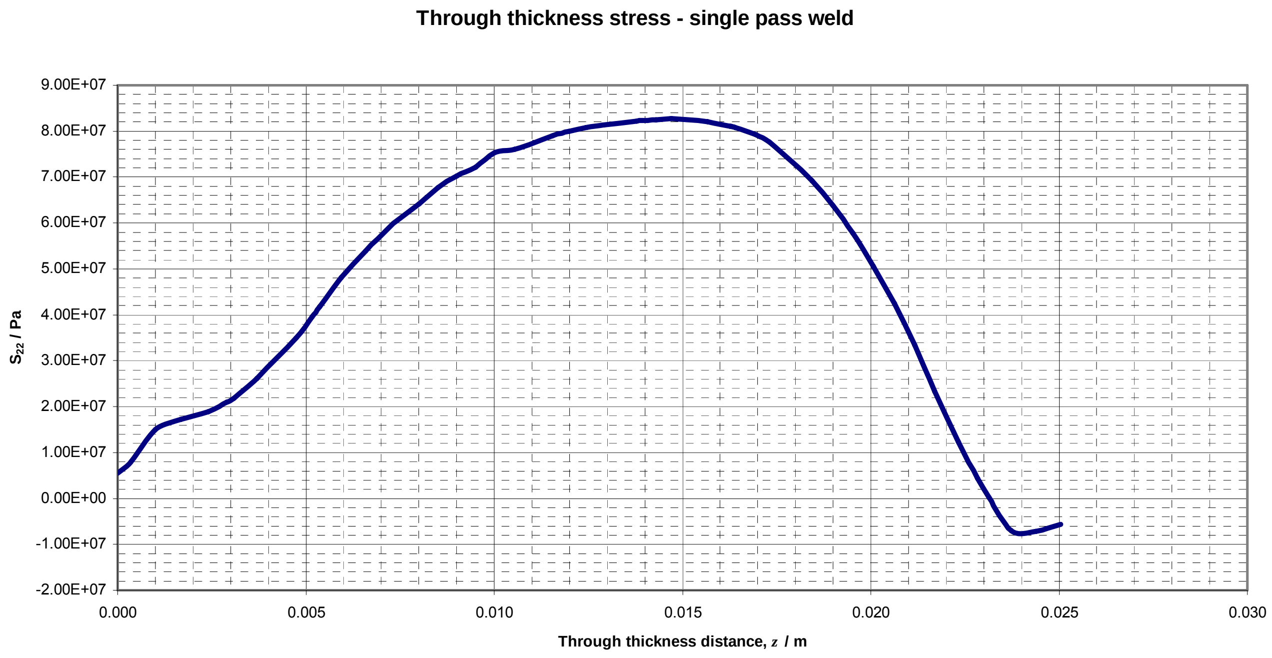
Through thickness stress - single pass weld
9.00E+07
8.00E+07
7.00E+07
6.00E+07
5.00E+07
4.00E+07
3.00E+07
2.00E+07
1.00E+07
0.00E+00
-1.00E+07
-2.00E+07
S22 / Pa
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Through thickness distance, z / m

Figure C. 20–

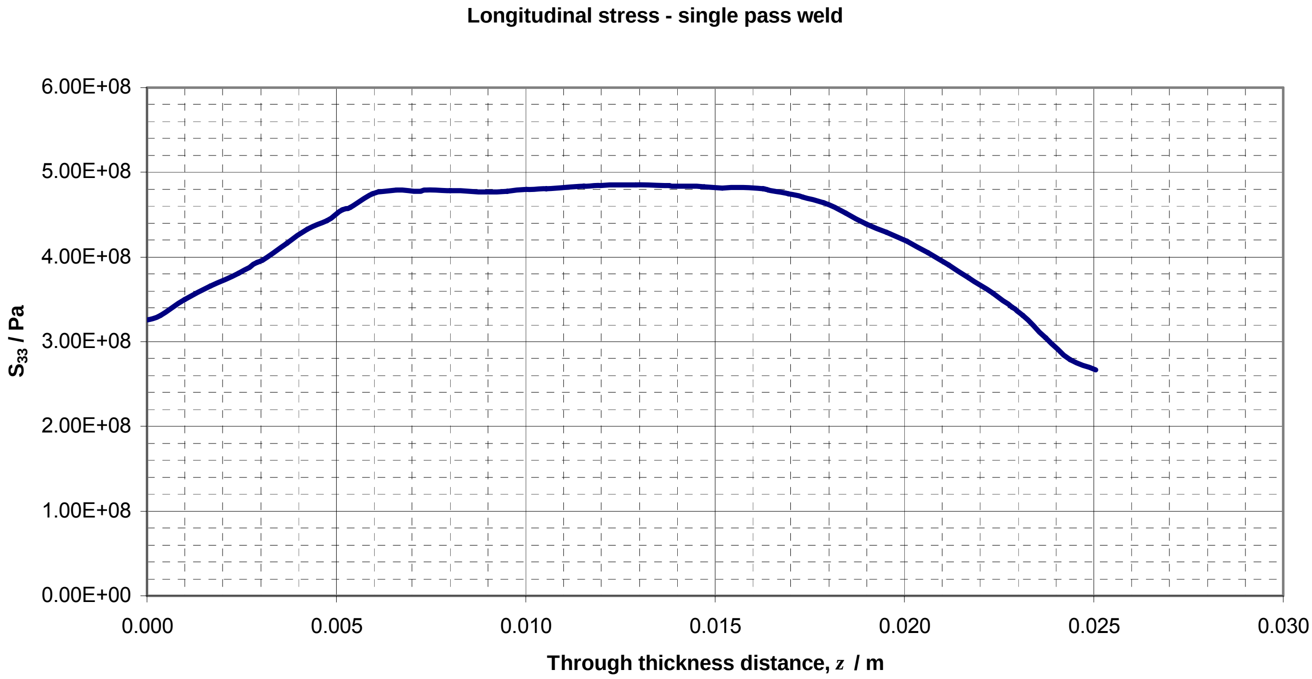
Longitudinal stress - single pass weld
6.00E+08
5.00E+08
4.00E+08
3.00E+08
2.00E+08
1.00E+08
0.00E+00
S33 / Pa
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Through thickness distance, z / m

Figure C. 21

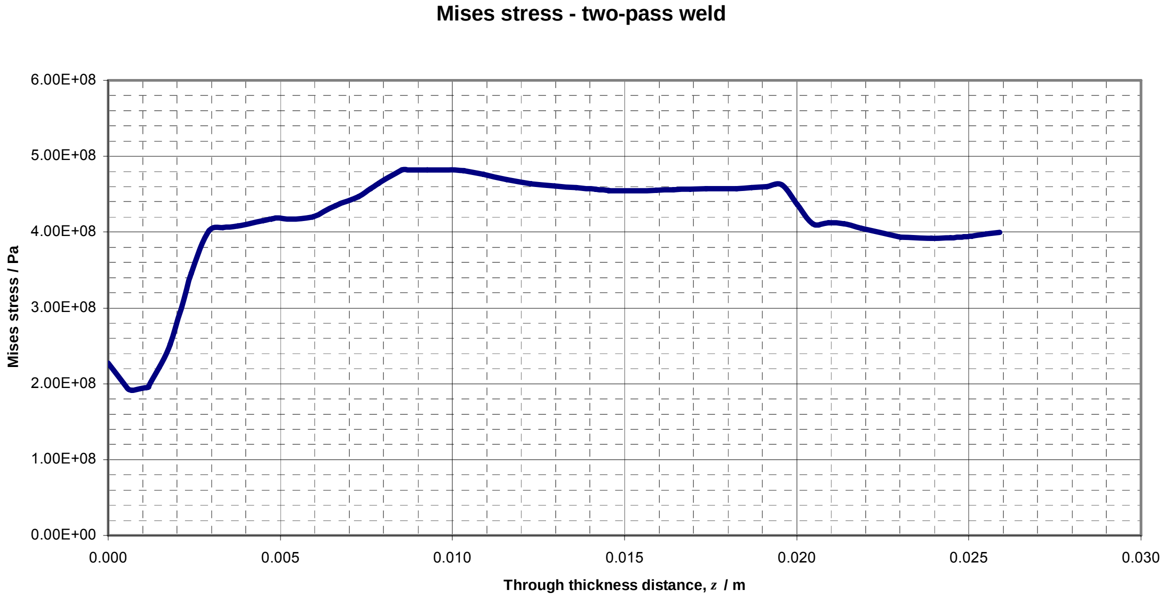

Figure C. 22

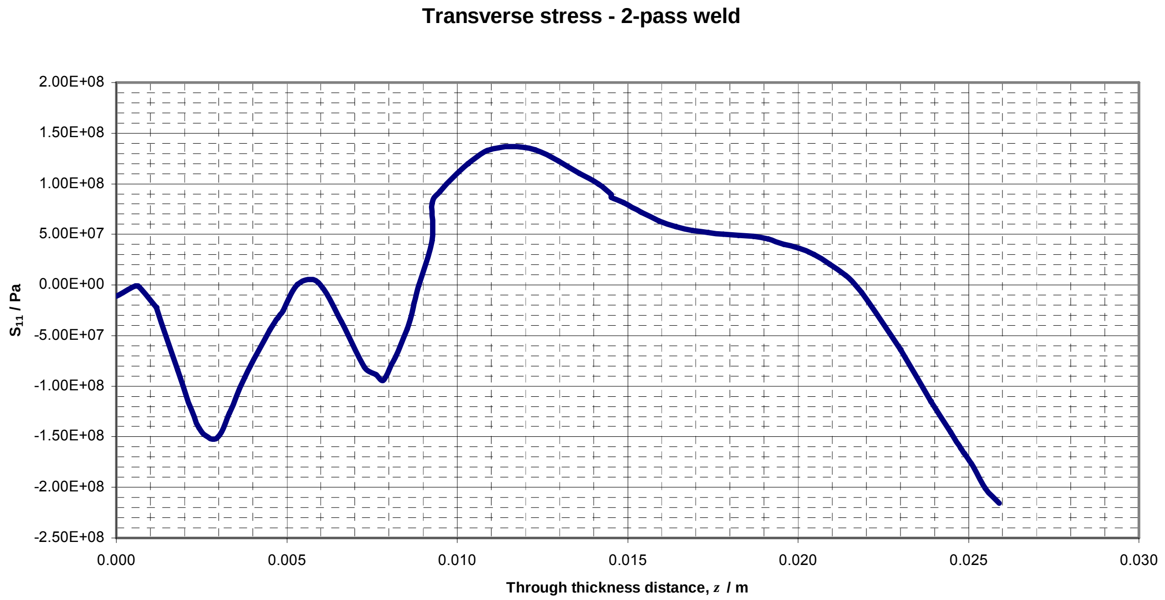

Figure C. 23

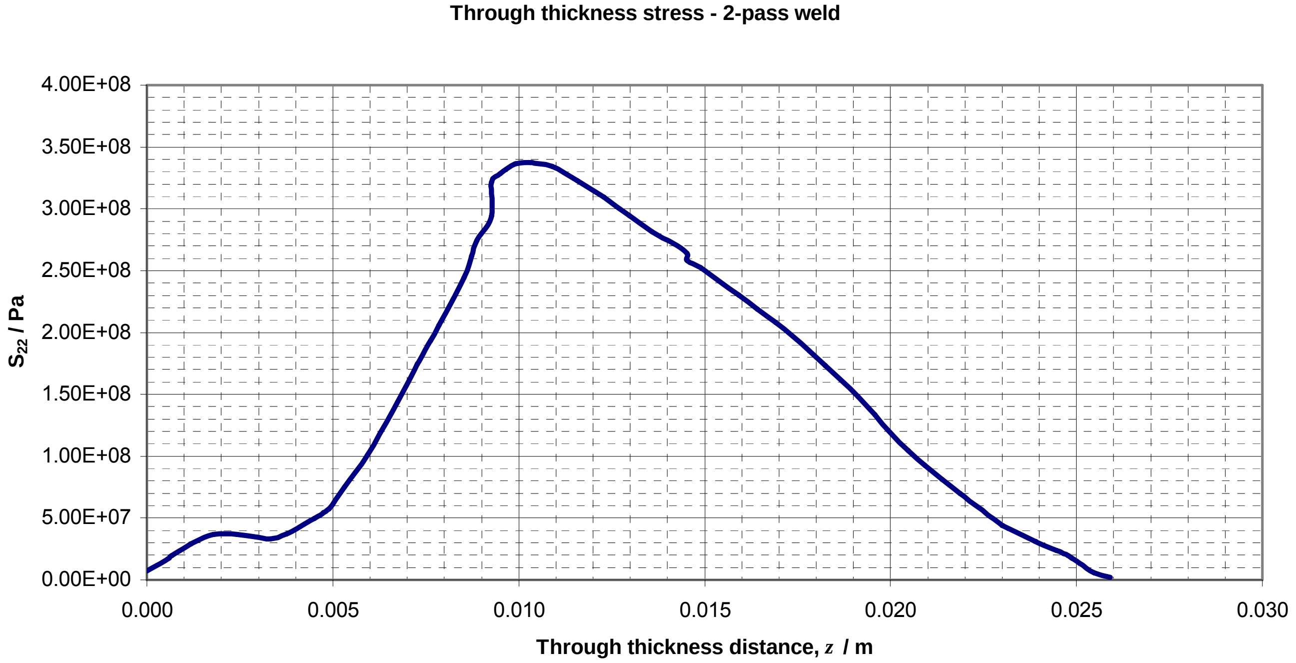

Figure C. 24

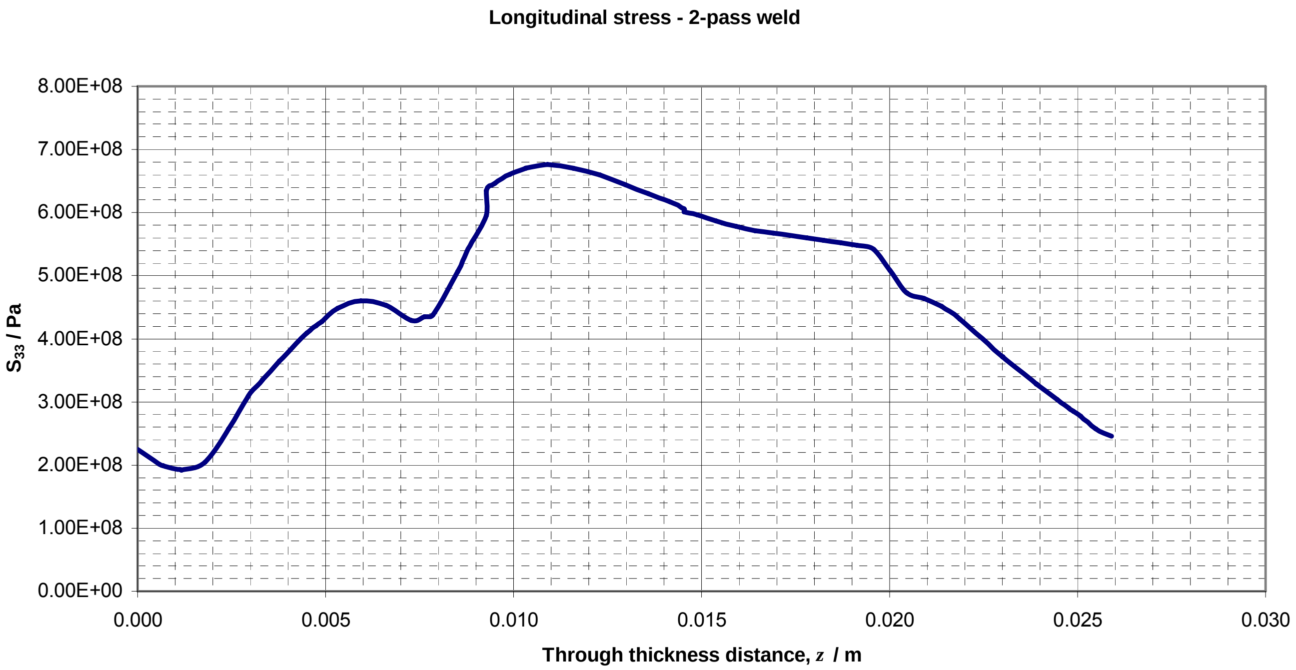

Figure C. 25

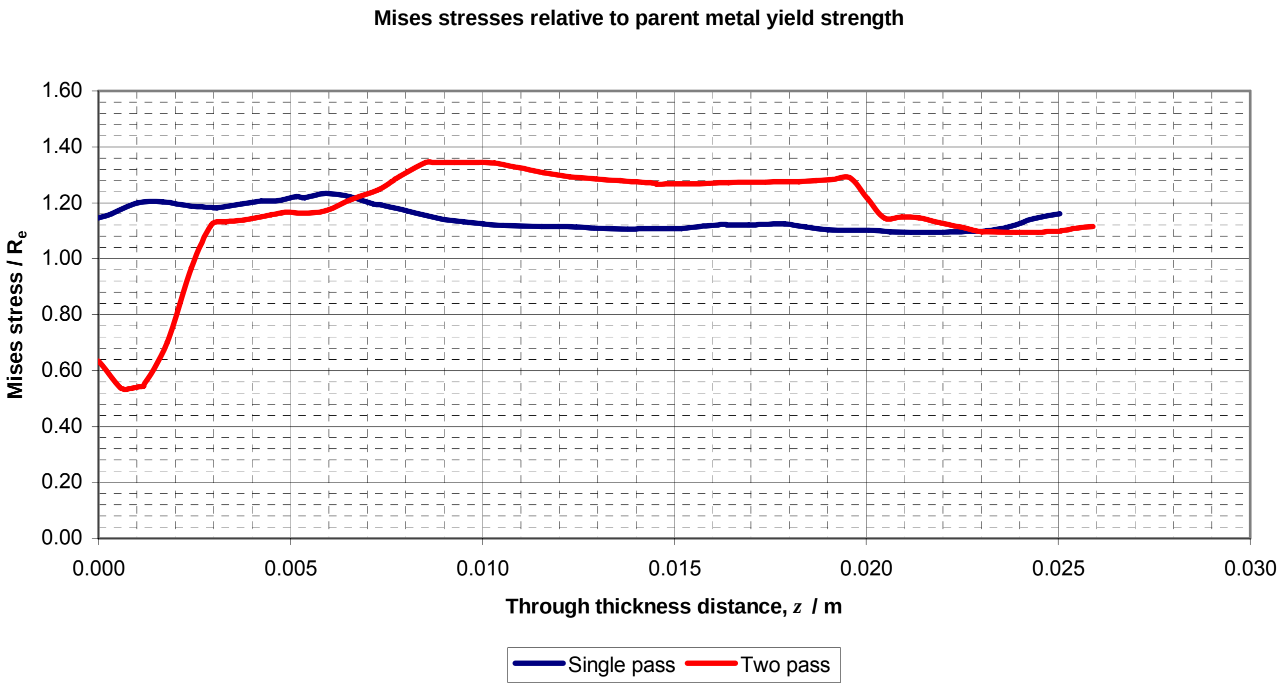

Figure C. 26

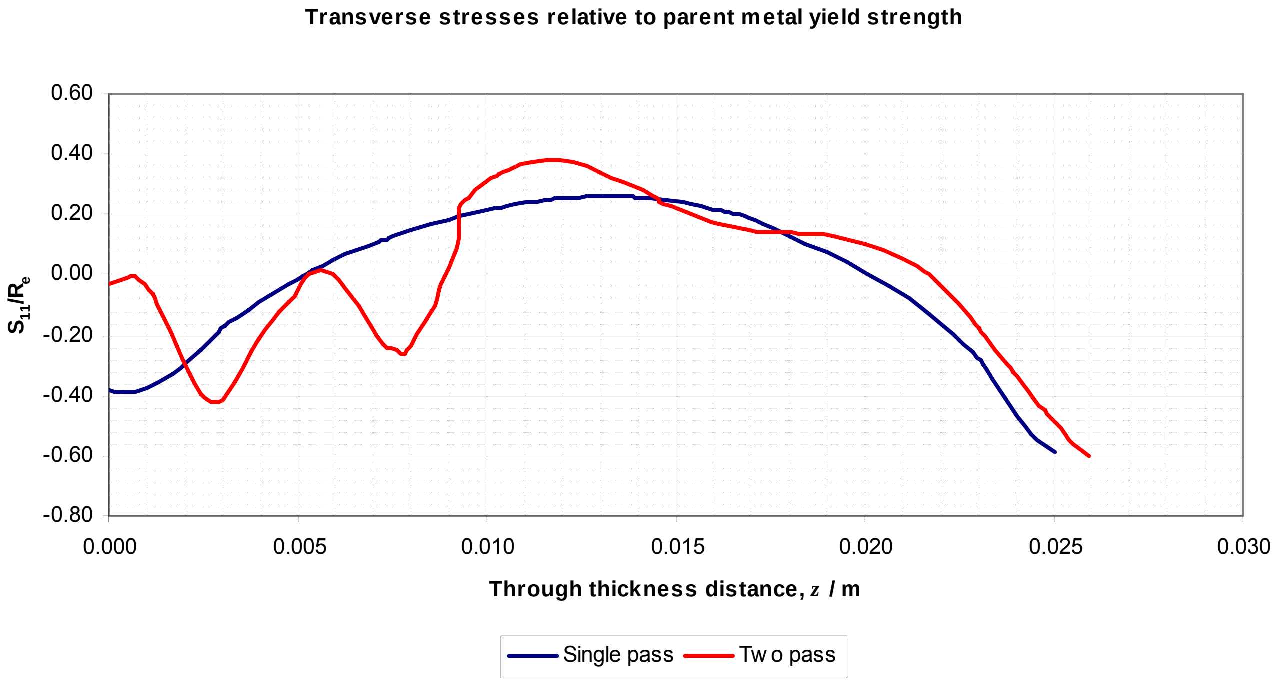

Figure C. 27

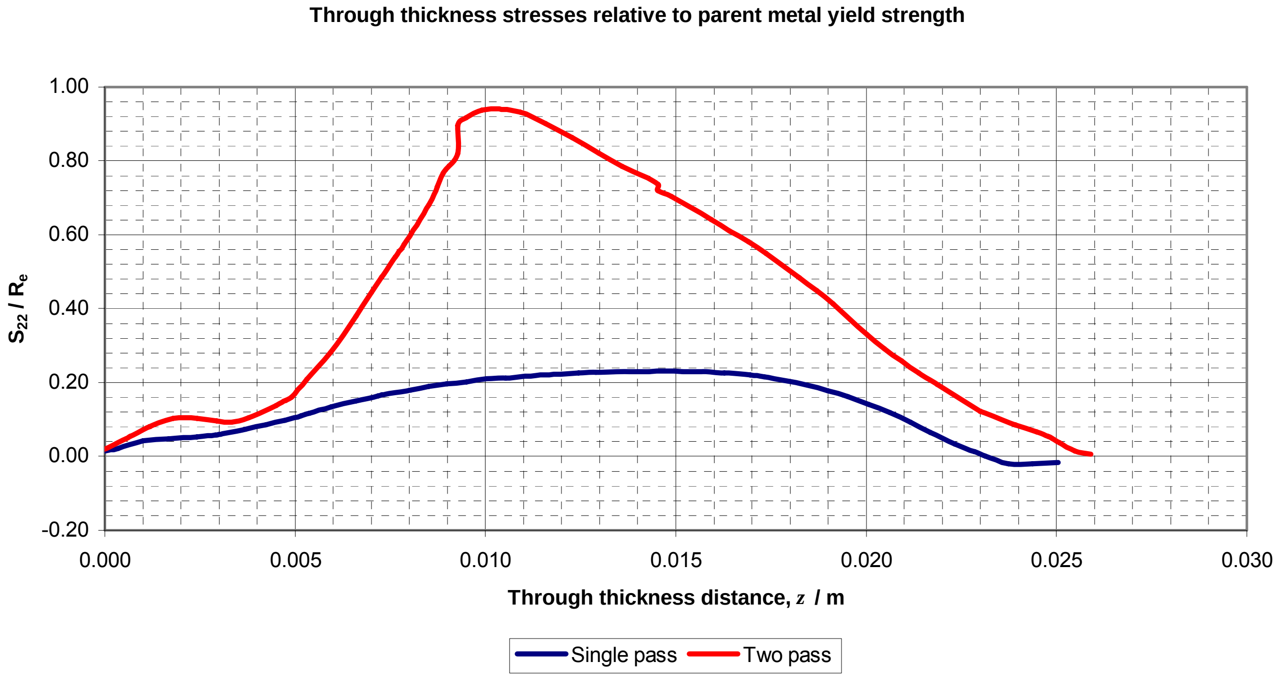

Figure C. 28

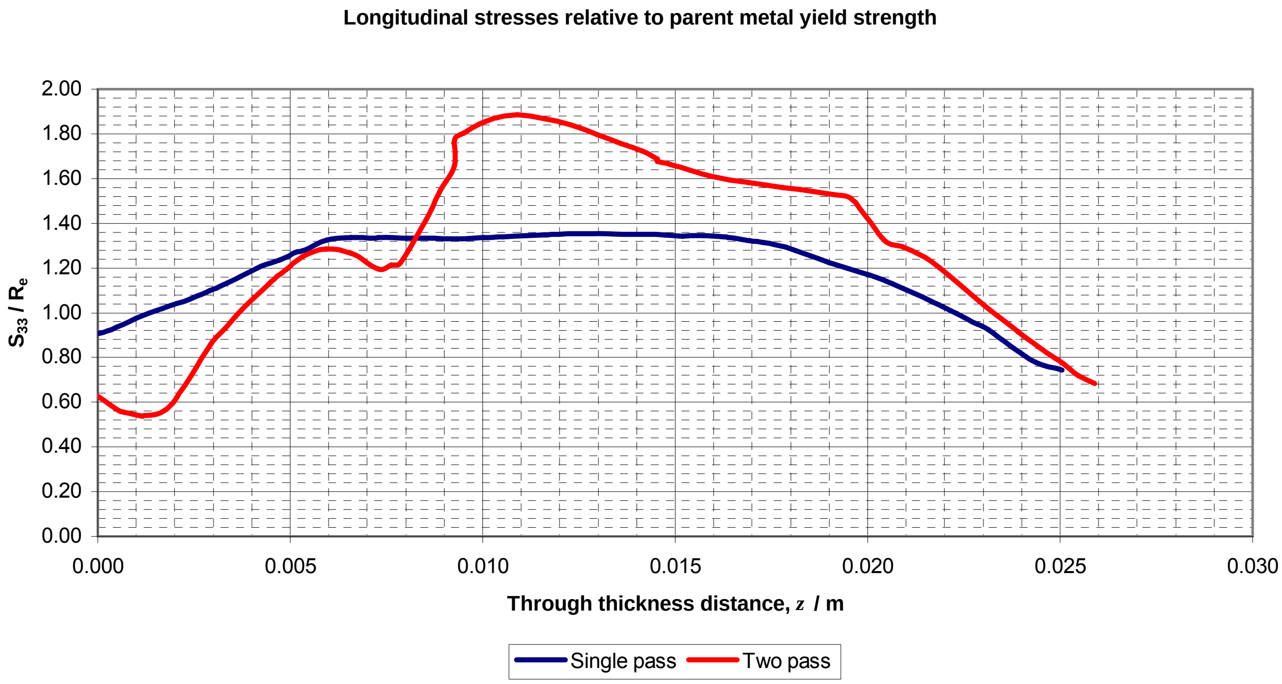

Figure C. 29

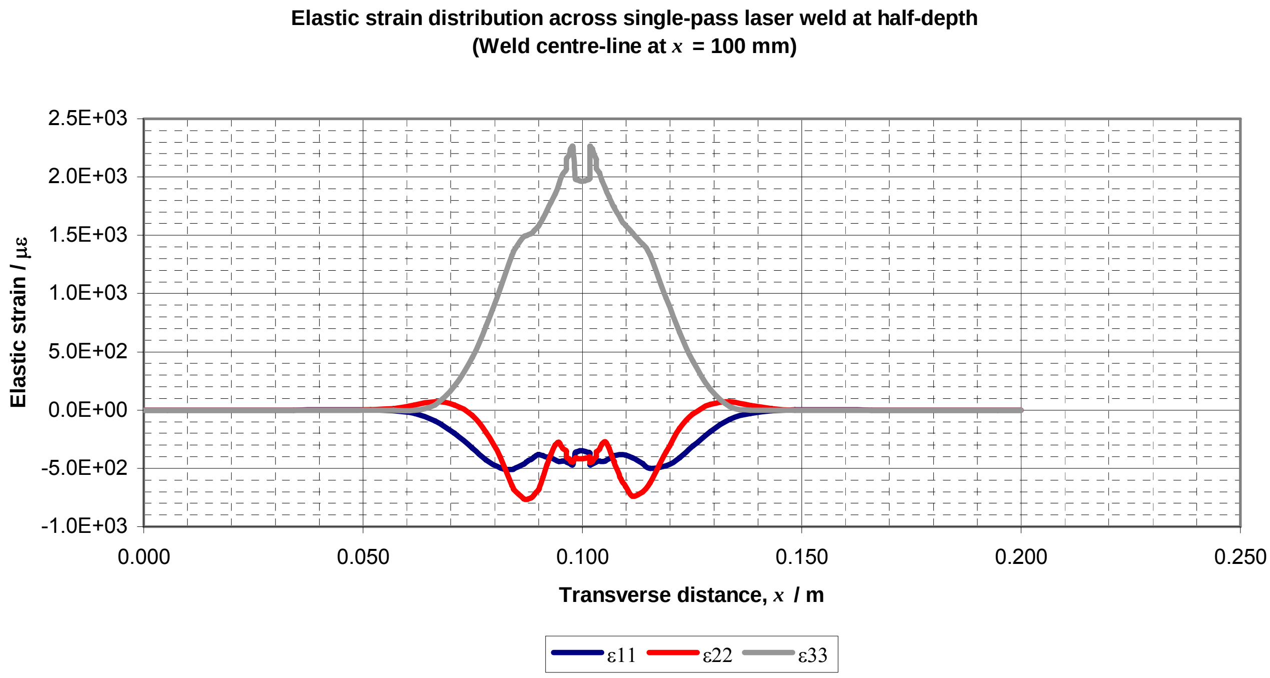
Elastic strain distribution across single-pass laser weld at half-depth
(Weld centre-line at x = 100 mm)
2.5E+03
2.0E+03
1.5E+03
1.0E+03
5.0E+02
0.0E+00
-5.0E+02
-1.0E+03
Elastic strain / με
0.000
0.050
0.100
0.150
0.200
0.250
Transverse distance, x / m
ε11
ε22
ε33

Figure C. 30

C.15.3 Bibliography

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