Proceedings of PVP2006-ICPVT-11
2006 ASME Pressure Vessels and Piping Division Conference
July 23-27, 2006, Vancoucer, BC, Canada

PVP2006-ICPVT-11-93808

Residual Stress Assessment in Japanese FFS Code for Pressure Equipment, HPIS Z101

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ABSTRACT

The High Pressure Institute of Japan published the first edition of Fitness for Service Assessment Procedure in 2001, HPIS Z101. Z101 is currently being revised and updated including the addition of Level 2 Assessment which involves more detailed evaluation regarding the structural integrity of cracked pressure vessels or piping systems than Level 1 Assessment. One of the notable revisions of Level 1 and the additions in Level 2 are the weld residual stress assessment of welded components. In the Level 1 assessment, the simplified residual stress distribution was defined in the current version. After publishing the current version, the committee has made an additional investigation into the residual stress assessment in existing FFS codes such as R6 and API 579 and has also compared the data in the technical literature on residual stress. The existent FFS code contains a certain degree of safety in residual stress assessment by making conservative structural integrity assessments for cracked pressure vessels and piping to prevent unexpected failure. However, the definition of residual stress profiles on the surface is controversial. In addition, some simplified definitions in the FFS codes do not always evaluate the measured weld residual stress safely.

In this paper, the contradictions and controversial issues regarding weld residual stress distributions are discussed. Furthermore, the draft of revised Z101 is explained.

Keywords; Residual Stress, Weld, Fitness for Service, Crack, Flaw

NOMENCLATURE

K: Material constant
q: Weld torch arc power
r_0: Dimension of surface residual stress zone
r_0*: Dimension of surface residual stress zone with 1.0 σ_{ys}^{mean}
t: Plate or pipe thickness
v: Weld travel speed
W: Width of weld at surface
η : Weld process efficiency
σ_f : Flow stress
σ_f^{mean} : Mean flow stress
σ_{uts}^{mean} : Mean ultimate tensile strength
$\sigma_{uts}^{\min}$: Specified minimum ultimate tensile strength
σ_{yp} : Yield strength of parent material
σ_{ys}^{mean} : Mean yield strength
$\sigma_{ys}^{\min}$: Specified minimum yield strength

INTRODUCTION

The High Pressure Institute of Japan (HPI) published the first edition of Fitness for Service Assessment Procedure, HPIS Z101, in 2001[1,2]. The assessment procedure contained only the Level 1 version, which is a simplified assessment procedure for evaluating the structural integrity of cracked pressure vessels and piping systems. Level 1 evaluates the allowable crack length based on comparison between Stress Intensity Factor (SIF) and Fracture Toughness, Kmat. In order to readily make the assessment, SIF is basically estimated from the crack length and the applied stress in Level 1. The applied stress contains the designed applied stress, i.e., allowable stress, and residual stress such as weld residual stress. The allowable stress was estimated from ultimate tensile strength with safety factors of 3.5 and 4 respectively in Level 1. In other words, HPIS Z101 Level 1 is applicable to the pressure equipments designed with safety factors of 3.5 or 4 regardless of industry, such as oil refining, gas industry and so on.

The High Pressure Institute of Japan has been updating Z101; Level 1 is being revised and a more accurate assessment Level 2 will be newly added. One of the notable changes in Z101 is the weld residual distribution. Since the SIF calculation includes residual stress, the required toughness in Level 1 assessment is consequently reviewed.

In revising the weld residual stress distribution, the existing FFS codes such as R6, BS7910 and API 579 [3-5] have been referred to. Both R6 and API 579 contain comprehensive weld stress distributions in their assessments. Both codes surveyed numerous experimental data and technical reports, and then define comprehensive residual stress distributions. These distributions do not exactly reflect the experimental or analytical data, but they cover the upper bound solution of referred data. Therefore, they should be conservative enough for making safe assessments.

The residual stress profiles on the surface in R6 Level 2 procedure is defined with consideration to welding conditions such as heat input, yield strength, and so on. The welding conditions are generally very important and greatly affect the weld residual stress distribution or maximum residual stress. However, the welding conditions are not always recorded precisely. It is consequently required to estimate weld residual stress without welding condition records.

API 579 assesses the residual stress profiles on the surface by means of thickness or the width of weld metal. The procedure seems to be more simplified and easy to use. However, it is not sufficiently conservative in some cases.

In revising the weld residual stress distribution of welded components in HPIS Z101 Level 1, R6 and API 579 were mainly referred to and compared with experimental data. The surface residual stress profile, the residual stress distribution through the thickness and the magnitude of the maximum residual stress were mainly estimated. The result was also utilized in defining the residual stress distributions of Level 2. The details of the comparison and the procedure to estimate the residual stress distribution in HPIS Z101 Level 1 and 2 are discussed in this paper.

RESIDUAL STRESS ASESSMENT IN HPIS Z101 LEVEL 1

HPIS Z101 Level 1 assessment is an initial conservative assessment and enables ready assessment [1,2]. The residual stress distributions in Level 1 are simplified and are applicable without detailed information regarding the welding conditions. However, the application is limited only to a few weld joint configurations such as plate butt welds, pipe seam welds and pipe butt welds because Level 1 is applicable only to configurations without stress concentration. Though the applicable welding methods are not specified in Level 1, the weld residual stress was estimated to the conventional weld procedures such as SAW, SMAW and so on.

The current version of Z101 Level 1 estimates the residual stress distribution in a welded component as follows [1,2].

- The residual stress distribution through thickness is uniform.
- The maximum residual stress is $0.6\sigma_{ys}^{mean}$.

Here, σ_{ys}^{mean} is a mean yield strength assumed by the following equation [1,4].

$$\sigma_{ys}^{mean} = \sigma_{ys}^{\min} + 69MPa \quad \text{------------------------------ (1)}$$

In equation (1), $\sigma_{ys}^{\min}$ is specified minimum yield strength. Since the actual yield strength is to be higher than the specified minimum yield strength of the material standard, it is not sufficiently conservative to use the specified minimum yield strength in assessing the residual stress. API 579 uses σ_{ys}^{mean} as actual yield strength in the assessment.

The magnitude of residual stress in current Level 1 assessment, $0.6\sigma_{ys}^{mean}$, was referred to from WES 2805[7] which is the assessment method for flaws in welded joints with respect to brittle fracture and fatigue crack growth. However, the coefficient of 0.6 is smaller than the experimental data and it is not conservative enough for assessing the structural integrity of cracked components. Both R6 and API579 estimate the maximum weld residual stress to be equal to the mean yield strength of the base metal or the weld metal.

Another issue to be considered is the surface profile of the residual stress. The surface profile of residual stress is not defined in the current Z101 Level l. The lack of surface profile sometimes confuses engineers when assessing the integrity of a cracked component. It is preferable to assign the surface residual stress profiles of residual stress.

After HPIS Z101 was published, the above issues were discussed and the committee at HPI reviewed the residual stress distribution in the Level 1 assessment. The review was conducted from the following viewpoints: the surface profiles of residual stress, the magnitude of residual stress and the residual stress distribution through the thickness. The effects of a PWHT were also inspected with the data in technical literature and the residual stress profiles in welded joint with PWHT were inherited in the revised version as a result. Therefore, this paper discusses the residual stress for an as-welded joint.

Surface residual stress profiles

R6 estimates the uniform residual stress distribution with a magnitude equal to the material yield strength in its Level 1 assessment [3]. The mean room temperature 0.2 % proof stress is recommended for the yield strength of ferritic materials and 1% proof stress of austenitic steels. While the R6 Level 1 assessment is simple and convenient to assess, it is very conservative.

The R6 Level 2 assessment defines the surface stress profiles and yielded zone according to the welding conditions [3]. For thick plate, the residual stress zone, r_0, is estimated from the following equation.

$$r_0 = \sqrt{\frac{K}{\sigma_{yp}} \cdot \frac{\eta q}{v}} \quad \text{------------------------------------(2)}$$

In the case of thin plate, the residual stress zone, y_0, is estimated as follows.

$$y_0 = \frac{1.033K}{\sigma_{yp}} \cdot \frac{\eta q}{vt} \quad \text{----------------------------------(3)}$$

Details of the definitions of thick plate and thin plate are mentioned in R6 [3]. Briefly speaking, a thick plate is a plate such as multi-pass welds and a thin plate is a plate such as a single pass or two-pass welds. The transverse residual stress profiles as a function of the plate thickness are also defined in some cases, such as the surface stress profile in plate butt welds.

Since R6 defines its valid geometry and welding conditions for Level 2 assessment of ferritic steel as shown in Table 1, the maximum surface residual stress zone, r_{0max} and y_{0max}, can be estimated from equation (2) or (3) with the maximum heat input condition and minimum yield strength of the parent material. Figure 1 shows the longitudinal weld residual stress zones, r_{0max} and y_{0max} in the case of plate butt welds of ferritic steel. R6 defines the same surface longitudinal residual zone in pipe seam welds as that in plate butt welds. The experimental data [8-10] have also been plotted in Figure 1.

According to Figure 1, the maximum residual stress zone of R6 Level 2, r_{0max} or y_{0max}, estimated from the validity range well covers the experimental residual stress zone.

API 579 does not include the residual stress distribution of simple plate butt weld joints [4]. Since the surface longitudinal weld residual stress zones of pipe seam welds can be treated as identical to that of butt welds, the surface residual stress zone of pipe seam welds defined as 0.75t in API 579 was plotted in Figure 1. The figure suggests that the surface weld residual stress zone defined as 0.75t, was too small in the case of thin pipe and too conservative for thick pipe. As a result, the surface longitudinal weld residual stress of plate butt welds in HPIS Z101 Level 1 was defined as r_{0max} in thick plate and y_{0max} in thin plate as shown in Figure 1.

Figure 2 shows the surface transverse residual stress zone estimated from R6 and experimental data [8-10] in the case of plate butt welds. In this case, the surface residual stress zone in R6 was defined as a function of plate thickness; 2t in restrained welds, t in unrestrained welds respectively. The experimentally measured residual stress zones in Figure 2 were higher than plate thickness "t" in the case of thin plate butt welds. According to this comparison, the surface weld residual stress zone was defined as 2t in HPIS Z101 Level 1 as shown in Figure 2. Figure 3 indicates the surface longitudinal residual stress zone of R6 in the case of pipe butt weld of austenitic steel and experimental data [11]. The maximum surface residual stress zone, r0max or y0max, was estimated from equation (2) or (3) and covers the experimental data, i.e., the surface transverse weld residual stress zone of plate butt welds was well estimated by r0max and y0max as well as the surface longitudinal weld residual stress zone as shown in Figure1.

As a result of these studies, r_{0max} in thick plate and y_{0max} in thin plate were adopted as a surface longitudinal residual stress zone in the case of plate butt welds and pipe butt welds in HPIS Z101 Level 1 as shown in Figure 1 and 3. The transverse residual stress of plate butt welds was defined as a function of plate thickness, 2t as shown in Figure 2.

Table 1 Validity ranges for as-welded residual stress distributions of ferritic steels in R6

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	-

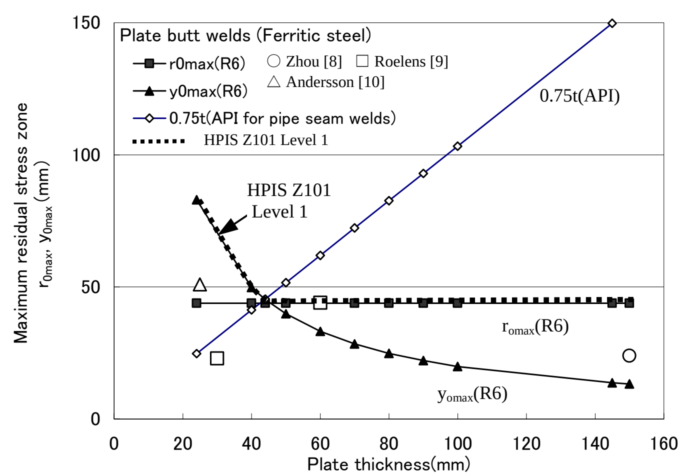


Fig. 1 Surface longitudinal weld residual stress zone in HPIS Z101 and experimental data of plate butt welds (API 579 indicates the surface weld residual zone in pipe seam welds)

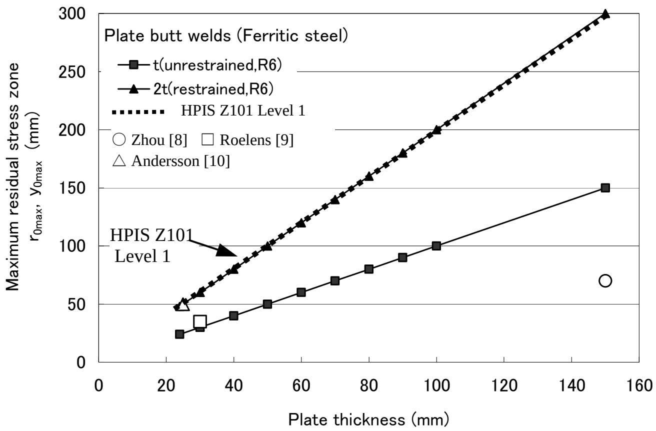


Fig. 2 Surface transverse weld residual zone in HPIS Z101 and experimental data in plate butt welds.

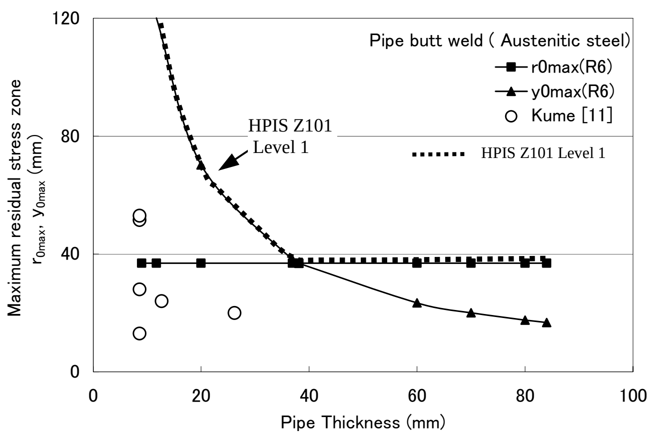


Fig. 3 Surface longitudinal weld residual stress zone in HPIS Z101 and experimental data in pipe butt welds as a function of pipe thickness

Residual stress distribution through thickness

In the current version of HPIS Z101 Level 1, the residual stress distribution through the thickness is uniform. Since Level 1 is a simple and conservative assessment, the approach is inherited in the revised version.

Magnitude of residual stress

The magnitude of weld residual stress is usually assumed to be equal to the mean yield strength or proof strength in the existing codes. But the mean yield strength of the parent material is not sufficient as the residual stress because of the work hardening and multiaxial effect. In addition, the yield strength of the weld material is generally larger than that of the parent material.

Figure 4 shows the experimentally measured weld residual stress distribution of plate butt welds for high tensile strength steel (HT-36) [10]. The yield strength of the parent material was 360 MPa and that of the weld metal was about 460 MPa. The magnitude of σ_x, the longitudinal residual stress in the weld width, was higher than the yield strength of the parent material. Such a high weld residual stress is sometimes observed in welds [8,12-15]. Besides, manufacturing defects are often embedded in the weld and tend to be a crack. Therefore, the revised Z101 Level 1 took into account the high residual stress in the weld.

Firstly, the mean yield strength of the weld metal calculated by equation (1) was defined as a magnitude of residual stress like R6 [3]. However, the specified minimum strength of the weld metal is not always available. Therefore, the mean flow stress estimated from the parent material is defined as a magnitude of residual stress in the weld metal when the specified minimum strength of the weld metal is not known. The mean flow stress is calculated by the following equation derived from the material data base analysis [6].

$$\sigma_f^{mean} = \frac{\sigma_{ys}^{mean} + \sigma_{uts}^{mean}}{2} = \begin{cases} 0.9\sigma_{ys}^{\min} + 174 \text{ (Ferritic steel)} \\ \sigma_{ys}^{\min} + 219 \text{ (Austenitic steel)} \end{cases} \quad \text{---------} (4)$$

σ_f^{mean} : mean flow stress

σ_{ys}^{mean} : mean yield strength of parent metal

σ_{uts}^{mean} : mean ultimate tensile strength of parent material

$\sigma_{ys}^{\min}$: specified minimum yield strength of parent material

In the case of Figure 4, the estimated mean flow stress from equation (4) was 436 MPa. The estimated mean flow stress was almost as same as the actual yield strength of weld metal, 460MPa. The peak stress was observed in weld metal in Figure 4, which was slightly higher than the mean flow stress. However, the effect of the peak stress was not so significant because the SIF was usually calculated average stress on the crack. It can be concluded that the mean flow stress is well estimated the residual stress in the welded joint.

In the case of austenitic steel such as type 304 or 316, the specified minimum yield strength and tensile strength in JIS [16] is 205MPa. The estimated mean flow stress from Eq. (4) was 424 MPa. The typical yield strength of weld metal of type 316 stainless steel is about 400-450 MPa [17]. Kume, et. al. measured the residual stress in the butt weld of type 304 stainless steel pipe and the maximum stress was 400MPa in the weld [11]. Eq. (4) is also available to estimate the mean flow stress of weld metal for austenitic steel.

According to those results, the mean flow stress of the parent material is available to estimate the residual stress in the weld when the specified minimum yield strength of weld metal is not known. In the case where the yield strength of the weld metal is lower than that of the parent material, it is recommended that the mean flow stress from equation (4) should be used instead of the yield strength of weld metal to make a safe assessment.

As a result of the above investigation, the revised HPIS Z101 Level 1 defines the weld residual stress zone on the surface as summarized in Table 2. Figure 5 shows the longitudinal weld residual stress profile on the surface in the case of plate butt welds and pipe seam welds. The magnitude of the residual stress in the weld is uniform and as high as the mean yield strength of the weld metal or the mean flow stress. The residual stress zone is defined as r_{0max} or y_{0max}. The magnitude of the weld residual stress in the parent material was divided into two zones. The as-welded residual stress in the center zone, r_0^*, is $1.0\sigma_{ys}^{mean}$ and that in the outer zone, r_0-r_0^*, is $0.6\sigma_{ys}^{mean}$. Therefore, the residual stress in the outer zone is the same as that in the current Level 1. The magnitude of the weld residual stress with PWHT component is $0.3\sigma_{ys}^{mean}$ in parallel to the welding direction, $0.2\sigma_{ys}^{mean}$ in perpendicular to the welding direction respectively. The residual stress distribution through the thickness is defined as uniform as well as the current Level 1.

Table 2 Weld residual stress zone and distribution in HPIS Z101 Level 1

PWHT	Welds	Direction to welding	Thickness	Distance from weld bond	
				r_0^*	r_0
without PWHT	Plate butt welds	Longitudinal	>=45.4	17.6	44.0
			<45.4	797/t	1992/t
		Transverse	-	0.8t	2.0t
	Pipe seam welds	Longitudinal	-	16.7	41.6
		Transverse	-	0.4t	1.0t
	Pipe butt welds	Longitudinal	>=33.2	12.9	32.2
			<33.2	426/t	1064/t
		Transverse	-	*(1)	
with PWHT	All	Longitudinal	$0.3\sigma_{ys}^{mean}$ in above residual stress zone		
		Transverse	$0.2\sigma_{ys}^{mean}$ in above residual stress zone		

t: Plate thickness (mm)

r_0^*: Zone in which residual stress is $1.0\ \sigma_{ys}^{mean}$ (mm)

r_0: Zone in which residual stress is $0.6\sigma_{ys}^{mean}$ (mm)

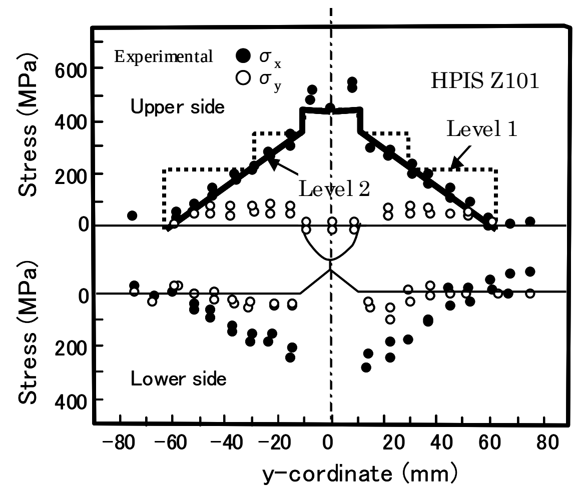
*(1): Uniform residual stress equal to mean yield strength is assumed in whole area

Note: Residual stress through thickness is uniform.
Residual stress in weld metal is mean yield strength of weld metal or mean flow stress of parent material.

RESIDUAL STRESS ASSESSMENT IN HPIS Z101 LEVEL 2

In the Level 1 assessment of HPIS Z101, the maximum residual stress zone is estimated from the validity ranges of the welding conditions and applicable without detailed welding information. In the Level 2 assessment, more information such as welding condition is required, but gives more accurate assessment with less conservative than Level 1.

Level 2 assessment will also include other weld geometry that were not included in Level 1 such as T-but weld and repair weld. However, these are still under investigation and the methodology is not mentioned in this paper.



σ_x : Longitudinal residual stress,

σ_y : Transverse residual stress

Fig. 4 Specified weld residual stress distribution in HPIS Z101 and measured weld residual distribution [10] on the surface in plate butt weld

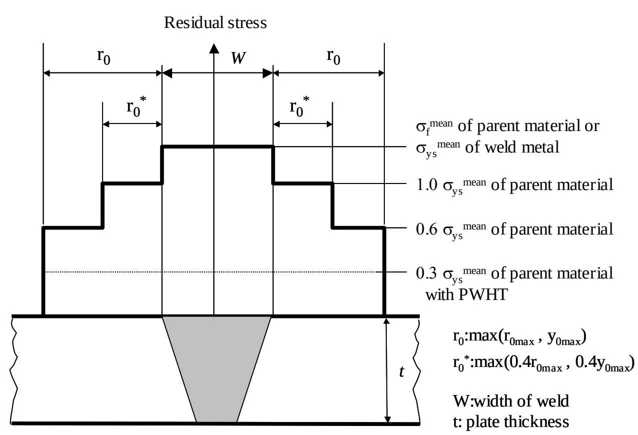


Fig. 5 Longitudinal weld residual stress profile on the surface in the case of plate butt welds and pipe seam welds (HPIS Z101 Level 1)

Surface residual stress profiles

The validity range of the welding conditions is taken into account in the Level 2 assessment. The residual stress zone is, namely, estimated from equation (2) or (3) with the welding conditions. If the welding conditions are unknown, Level 1 assessment should be applied.

Level 2 assumes a trapezoid residual stress profile on the surface, as shown in Figure 4.

Residual stress distribution through thickness

The Level 2 assessment can also take into account the residual stress distribution through the thickness. Most of existing FFS codes adopt the residual stress distribution through the thickness defined as a polynomial function or uniform stress. R6 and API 579 take into account the asymmetry caused by the groove geometry such as single sided welds (V-groove) and double sided welds (X-groove).

Figure 6 schematically explains the difference in surface longitudinal residual stress on the top surface and bottom surface of thick plate butt welds. According to R6, the surface residual stress profile on side A1 was estimated as shown by the solid line. On the other hand, the surface longitudinal residual stress profile on side A2 was estimated as shown by the dotted line. In the case of a plate butt weld of ferritic steel, the distribution of residual stress through the thickness (A1-A2) was assumed to be uniform. Therefore, the residual stress at point A2 should be the same as that at point A1, which was the top point corresponding to A2. However, the surface residual profiles were different from each other and the magnitude of residual stress at A2 did not coincide with that at point A1. Most equations adopted in the existing FFS codes induce the same residual stress at the top surface and bottom surface. A contradiction exists between the surface stress profile and the stress distribution through the thickness.

In HPIS Z101 Level 2, the residual stress distribution through the thickness linearly interpolates the residual stress on the surfaces. The schematic distribution is shown in Figure 7. The definition is simple but well covers the residual stresses of both surface profiles and through-thickness distribution. The estimation does not include the reduction in residual stress at mid-thickness. However, the measured residual stress distribution can be used in Level 2 if it is available.

Residual stress distribution on the surface

As shown in Figure 4 and Figure 7, the trapezoid residual stress distribution is adopted in Level 2 instead of the step-like profile of Level 1. The maximum residual stress is the same as that of Level 1. The residual stress in the width of the weld is the mean yield strength of the weld metal or the mean flow stress of the parent material. The maximum stress at the bond is the mean yield strength of the parent material. It decreases linearly toward the end of the residual stress zone, which is separated from the bond by r_0.

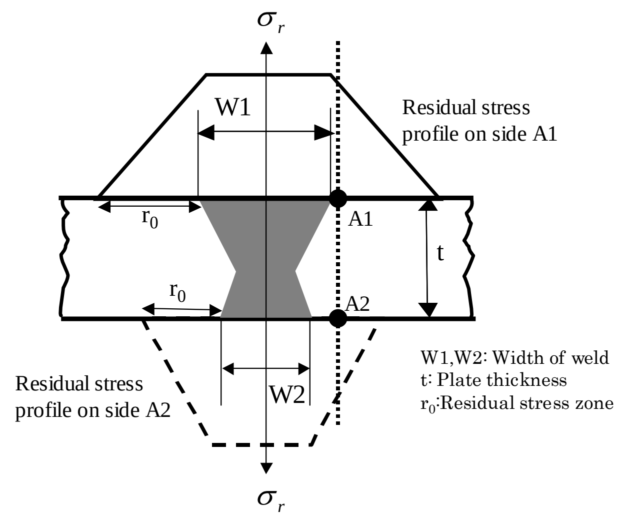


Fig. 6 Schematic profile of surface residual stress at top surface and bottom surface of thick plate (R6)

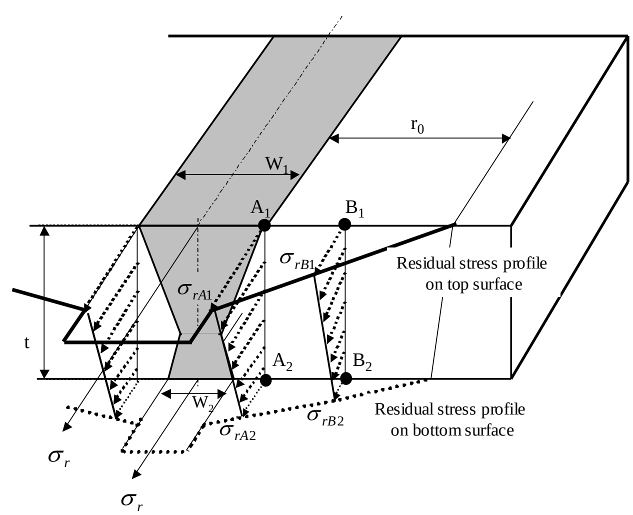


Fig. 7 Schematic longitudinal residual stress distribution through thickness in plate butt weld (HPIS Z101 Level 2)

SUMMARY

The weld residual stress distribution as a welded component was investigated for updating the Fitness for Service assessment, HPIS Z101, published by the High Pressure Institute of Japan. By delving into the FFS code together with experimental data and numerical data, Z101 defined the simplified residual stress distribution in Level 1 and comprehensive distribution in Level 2. The features of HPIS Z101 are as follows.

Level 1

- The residual stress zone on the surface is defined with consideration to the welding condition.

- The residual stress distribution is uniform though the thickness.
- The maximum stress is defined as the mean yield strength of the weld metal or the mean flow stress in the width of weld.
- The residual stress zone is divided into three zones in accordance with the distance from the center of weld.

Level 2

- The residual stress zone is specified according to the welding conditions.
- The trapezoid shape residual stress profile is adopted on the surface.
- The linear interpolation is used to define the residual stress distribution through the thickness.

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