

Analysis of Residual Stress Distribution in Welded Joints Depending on the Restraint Intensity

Boellinghaus, Th.; Kannengiesser, Th.; Neuhaus, M.; Florian, W.

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Abstract

To avoid cracking of welds it is important to know the stress distribution induced by the joining process. The intensity of restraint R_{Fy} , which is a measure of the shrinkage restraint counteracting the weld, is of high importance for the general stress condition expected after welding and solidification of the structure. Welding experiments using the IRC-Tests (Instrumented Restraint Cracking) were carried out on lab specimens with different intensities of restraint. First the residual stress distribution over the weld was determined for different restraint intensities by means of the incremental hole drilling method and was then compared with the reaction force F_r . With regard to transferability, component welding tests are evaluated with consideration of the reaction force distribution and the reaction stresses dependant upon the intensity of restraint. The material used in the tests was fine-grained structural steel P460ML1 and a matching filler material. The influence of phase transformation of the base and filler material on the transverse and longitudinal residual stresses produced across the weld was initially analyzed with respect to the effect of an external restraint. The residual stresses transverse to the weld are presented as a function of different restraint intensities and compared to component welds. In addition, residual stress measurements were carried out after specimen relief. Furthermore it is shown, how these experimental results can enter numerical simulations of complex welds, thus increasing the safety and reliability of welded structures.

Effect of Intensity of Restraint:

Shrinkage Restraint

global
Support effect/ reaction force of the restraint by hindered contraction

Scope:
Substantial volume respectively cross-sectional part of the welded construction

local
Inhomogeneous changing of the weld volume and the adjacent base material

Scope:
Range and vicinity of the weld

IRC-Test build up

The restraint intensity R_{Fy} represents the resilience of the surroundings related to the joint length. It is made up of the structural stiffness of the specimen and the stiffness of the surrounding construction, i.e. a combination of global and local shrinkage restraint.

Reaction forces and stresses

Reaction forces and stresses transverse to the weld depending on the restraint intensity

Stress related to the root weld
 $\sigma_1 = 380 \text{ MPa}$
 $\sigma_2 = 317 \text{ MPa}$
 $\sigma_3 = 215 \text{ MPa}$

$R_{Fy} = 2,39 \text{ kN/(mm}^2\text{mm)}$
 $R_{Fy} = 3,36 \text{ kN/(mm}^2\text{mm)}$
 $R_{Fy} = 5,62 \text{ kN/(mm}^2\text{mm)}$

- Increasing reaction forces F_r with increasing intensity of restraint R_{Fy}
- Maximum local reaction stress in the weld σ_1 after welding and cooling to roomtemperature

Welding residual stresses

Residual stresses transverse to the weld σ_y^E for one-layer welds against the restraint intensity R_{Fy}

- Increase of the residual stresses transverse to the weld σ_y^E depending on the restraint intensity R_{Fy}

Numerical simulations of typical weld joints

Quantification of the restraint intensity of pipe and plate welds with the help of the finite element methode

Plate / butt joint **Pipe / butt joint**

Geometries of the three dimensional finite element models:
 Plate/ Pipe thickness: 16 mm to 30 mm
 Weld length : 100 mm to 500 mm
 Clamping length : 110 mm to 1000 mm

Intensity of restraint [kN/mm²mm]

Plate (Wall) thickness [mm]

Weld length [mm]

Clamping length: 110 mm

- With equal component thickness and weld length, pipe constructions generally show larger intensities of restraint than plate constructions
- Regarding plates, the intensity of restraint is increasing with growing plate thickness
- The intensity of restraint of pipes with constant weld length (diameter) is increasing with higher wall thickness. Longer welds (larger diameters) cause lower intensities of restraint

Effect of Phase Transformation:

- Because of different temperature behaviour and phase changing conditions the rising of the residual stress is depending on the plate thickness H
- With increasing plate thickness, the ratio of residual stress to intensity of restraint decreases, thus resulting in an inversely proportional relationship to the ratio of plate thickness

Residual stress σ_y^E [MPa]

Intensity of Restraint R_{Fy} [kN/mm²mm]

Plate thickness $H_1 = 16 \text{ mm}$
 Plate thickness $H_2 = 30 \text{ mm}$

$\alpha_1 = \frac{H_2}{H_1}$
 $\alpha_2 = \frac{H_1}{H_2}$

Effect of Stress Relieving:

Load history of real component test weld

Force [MN]

Time [sec]

72 MPa 431 MPa

Approach to the real component test weld:

- Measurement of residual stresses σ_y^E transverse to the weld considering the intensity of restraint R_{Fy}
- Determination of the residual stress distribution after relieving the welded component
- Quantification of the residual stresses caused by the construction, the production process, and the type of material
- Influence of loading up to the yield strength on the welding residual stresses

Welding residual stresses $\sigma_x(y)$ and $\sigma_y(y)$ transverse to the weld

1 after welding and cooling of the specimen under restraint

2 after relieving the specimen

3 after loading to the yield strength $R_p(BM)$ and subsequent unloading

Transverse residual stress $\sigma_y(y)$

Longitudinal residual stress $\sigma_x(y)$

- Typical distribution of longitudinal and transverse residual stresses after cooling to room temperature because of inhomogeneous phase transformations and shrinkage
- Characteristic maximums of tensile residual stress in the heat affected zone (HAZ)
- Local exceeding of the yield limit of W/BM due to superposition of reaction stresses with shrinkage restraint
- Distinct dips of the residual stresses in the center of the weld due to phase transformation
- Significant reduction of the transverse residual stresses to 300 MPa due to specimen release
- Transverse residual stresses in the center of the weld (dips) are independent of the specimen release
- Longitudinal residual stresses are nearly independent of the specimen release
- Change of the residual stress distribution in the center of the weld due to plastic bending deformation at the top and bottom of the specimen during release
- Mechanical stretching and subsequent relieving of the specimen in transverse direction leads to an explicit reduction of the overall level of residual stress
- Reduction of the maximum tensile transverse residual stresses in the HAZ of approximately 90% in comparison to the fixed state
- Dips in the transverse residual stresses in the center of the weld are nearly independent of the load history
- Expectedly longitudinal residual stresses show no direct dependency of the load history in the transverse welding direction. High maxima of tensile residual stress appear in the HAZ with distinctive dips