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Research

Mechanisms important for material modelling in weld residual stress analysis

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SSM perspective

Background

The prediction of weld residual stresses (WRS) is very complex as many mechanisms and phenomena influence the development of WRS during welding. For accurate prediction, the constitutive material models used are essential and must be able to describe the material response of the weldment constituents. For example, selection of a material model should only depend on material behaviour and not on other parameters, mechanisms or modelling techniques. Thus, before constitutive models for welding simulations can be further developed, the interaction between all essential mechanisms and phenomena influencing WRS, and their respective impact on WRS, must be understood.

The present study aims to investigate mechanisms and phenomena related to welding and WRS. The purpose is to understand which mechanisms and phenomena that need to be considered for reliable predictions and how this knowledge should be taken into account in the material modelling.

Results

Mechanisms and phenomena are explained and their development of WRS during welding are studied. Consequently, some mechanisms and phenomena are pointed out as more important than other for how WRS develop. To improve knowledge and accuracy in WRS predictions some mechanisms and phenomena need to be further investigated.

Relevance

The work has increased the understanding for how mechanisms and phenomena influence the development of WRS. Moreover, the increased knowledge can lead to improved material models and accordingly more reliable predictions of WRS

Need for further research

High temperature mechanisms as recovery, recrystallization and creep are modelled by use of an annealing function. Today, a binary function where full annealing occurs when the temperature exceeds a predefined temperature is used. However, experimental data suggests that annealing should occur within a specific temperature span. An improved annealing function is further investigated in research project SSM2018-5270.

Project information

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Summary

The physics of welding is very complex. Many mechanisms and phenomena influence the development of WRS during welding. It is not completely clear which of them that is of most importance and which of them that has a minor impact.

In prediction of WRS, the constitutive material models used are essential. For accurate predictions, the models must be able to sufficiently well describe the material response of the weldment constituents. Selection of a material model should only depend on the material behaviour and not on other parameters, mechanisms or modelling techniques. For example, accurate WRS predictions for a weld should not require different material models if the simulation is done in 2D or 3D. Thus, before constitutive models for welding simulations can be further developed, the interaction between all essential mechanisms and phenomena influencing WRS, and their respective impact on WRS, must be understood.

In this report, mechanisms and phenomena related to welding and WRS are investigated. Focus is on both physics and simulation. The purpose is to understand which mechanisms and phenomena that need to be considered for reliable predictions of WRS and how this knowledge should be taken into account in the material modelling. Some mechanisms are pointed out for further investigation, i.e. annealing (recovery, recrystallization, creep), thermal and mechanical degree of constraint (2D vs 3D simulations), phase transformation and anisotropy. Suggested work involves experimental activities, constitutive material modelling and numerical predictions of WRS.

Sammanfattning

Svetsningens fysik är mycket komplex. Flera mekanismer och fenomen påverkar utvecklingen av svetsegenspänningar under svetsningen. Vilka av dessa som har störst inverkan och vilka som har mindre är inte fullt klarlagt.

Vid prediktering av svetsegenspänningar är de konstitutiva materialmodellerna väsentliga. Modellerna behöver tillräckligt väl kunna beskriva materialbeteendet för svetsens ingående komponenter. Val av materialmodell ska enbart bero på materialets beteende och inte på andra parametrar, mekanismer eller vald modelleringsteknik. Noggranna predikteringar av svetsegenspänningar för en svets ska exempelvis inte kräva olika materialmodeller beroende på om analyserna görs i 2D eller 3D. Innan befintliga materialmodeller för svetssimulering kan vidareutvecklas måste interaktionen mellan väsentliga mekanismer och fenomen som inverkar på svetsegenspänningarna, och deras respektive inverkan på svetsegenspänningarna, förstås.

I denna rapport undersöks mekanismer och fenomen relaterade till svetsning och svetsegenspänningar. Fokus ligger på fysiken och simuleringar. Syftet är att förstå vilka mekanismer och fenomen som behöver beaktas för tillförlitliga predikteringar av svetsegenspänningar samt förstå hur denna kunskap ska användas vid materialmodellering. Ett antal mekanismer pekas ut för fortsatta studier. Dessa är annealing (återhämtning, rekristallisation, krypning), graden av termisk och mekanisk inspänning (2D vs 3D simuleringar), fasomvandling och anisotropi.

Föreslaget arbete innefattar experiment, konstitutiv materialmodellering och numeriska beräkningar av svetsegenspänningar.

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Nomenclature

ε_{ij}	[-]	strain tensor
σ_{ij}	[Pa]	stress tensor
σ_{11}	[Pa]	normal stress in radial direction
σ_{22}	[Pa]	normal stress in axial direction
σ_{33}	[Pa]	normal stress in hoop direction
R_i	[mm]	inner radius of pipe
R_m	[mm]	mean radius of pipe
b	[mm]	height of weld bead
t	[mm]	thickness of pipe
T	[ºC]	temperature
CL		centre line of weld
DOF		degree of freedom
FE		finite element
FEM		finite element method
HAZ		heat affected zone
PEEQ		equivalent plastic strain
PWHT		post weld heat treatment
SCC		stress corrosion cracking
WPS		welding procedure specification
WRS		weld residual stresses

1. Introduction

1.1. Background

Welding of a steel component involves different physical processes. Interaction between mechanical, thermal and metallurgical phenomena in a temperature range from room to melting temperature makes the physics of the welding process very complex.

A weldment can be divided into different regions. With respect to chemical composition, a weldment consists of mainly three regions, i.e. weld, fusion line and parent material. The fusion line is clearly the smallest one consisting of a mixture of weld and base material. From a microstructural perspective, a weldment consists a number of different parts. One bead itself can contain various microstructures created during the solidification phase. Also the HAZ region contains a number of different microstructures. Here, different thermal cycles, depending on distance to the fusion line, cause a varying microstructure across the HAZ. Coarse-grained, fine-grained and intercritical HAZ are such examples. Finally, from a mechanical point of view, a weldment can be divided into regions in a third way. For a multi-bead weld, the evolvement of plastic hardening caused by cyclic plastic deformation is of importance for the mechanical properties. Another example is the influence of recovery and recrystallization on plastic hardening during a thermal cycle at elevated temperature.

It is obvious that the chemical composition influences both the microstructure and the mechanical properties in the weldment region. The microstructure furthermore influences the mechanical properties. The evolution of microstructure and the mechanical properties are influenced by the welding procedure, weld geometry, geometry of the welded component and thermal constraints. In addition, the mechanical constraints during welding influence the mechanical characteristics for the weldment.

This brief introduction to the physics of welding reveals its complexity caused by the different phenomena involved and their interaction. This form the basis for the objective with this project which is to investigate how constitutive material models can be improved to increase the accuracy in numerical prediction of weld residual stresses.

Accurate prediction of weld residual stresses (WRS) is of importance in assessing structural integrity of welded components. Regarding damage mechanisms, such as stress corrosion cracking (SCC), WRS often control the rate of crack propagation. Welding of steel structures inevitable results in WRS and welding deformation. In general, the more the pieces are constrained during welding, the higher the residual stresses get. On the other hand, if the pieces are free to move during welding, welding deformation is maximised.

WRS are a result of misfit of local regions in the weldment and its vicinity during and after welding. Rapid thermal expansion and contraction in a structure with constraints cause inelastic deformation to occur, which after cooling results in elastic strains in the weldment region. These elastic strains might be further increased with a difference in thermal expansion coefficient between the weld and the parent material. The residual stress directly corresponds to developed elastic strains.

The material models used for numerical prediction of WRS should be as simplified as possible without losing accuracy in predictions. The reasons for this are many. For example, experimental testing of the weldment constituents would be extremely comprehensive if each phenomena had to be captured in the range from room to melting temperature. Another reason is that the mathematical modelling would be extremely complex if all phenomena had to be considered explicitly. It is thus a challenging task to choose and develop material models for accurate prediction of WRS.

1.2. Purpose of project

The purpose of this project is to enhance the understanding of how different mechanisms and phenomena influence WRS in weldments. Based on this knowledge, steps are identified for improved constitutive modelling and thereby also more accurate WRS predictions.

2. Parameters influencing material modelling in weld residual stress analysis

Parameters influencing weld residual stresses (WRS) can be divided into four main groups as shown in Figure 2-1. The effect of parameters within these groups are all related to thermal, mechanical and/or metallurgical phenomena in one way or another.

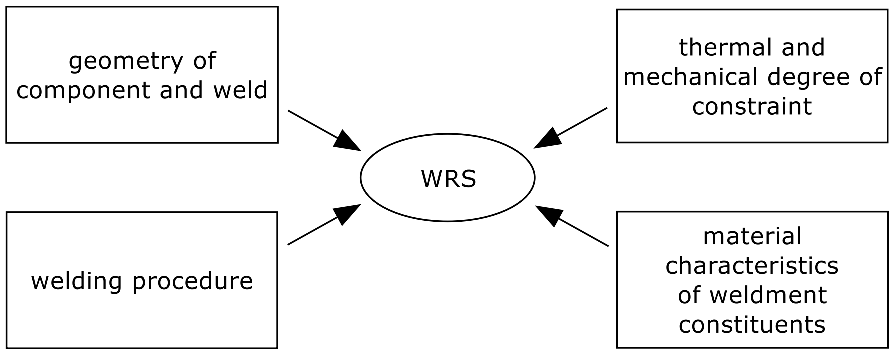

Figure 2-1: Parameter groups influencing WRS.

Each group comprises specific parameters such as:

i. geometry of component and weld: *R*, *t*, *R/t*, type of weld, local geometry of weld, global geometry of welded component, etc.,
ii. welding procedure: welding method, number and size of beads, sequence in deposition, heat input, interpass temperature, PWHT, etc.,
iii. thermal and mechanical degree of constraint: global and local effects, etc.,
iv. material characteristics of weldment constituents: differences between weld and parent material, type of plastic hardening, type of cyclic plastic hardening, distortion of yield surfaces, influence of temperature on hardening, effects of multiaxiality, behaviour at elevated temperature, phase transformation, etc.

The large number of influencing parameters and their mutual relationship result in a very high degree of complexity in understanding how WRS develop during welding. In addition, as welding comprises temperatures ranging from room to melting temperature, it is extremely challenging to experimentally capture all physical phenomena involved in the welding process. Thus, the basis for predicting WRS by numerical simulations cannot be fully complete.

Numerical simulation of WRS always requires assumptions and simplifications. Main reasons are:

i. lack of experimental data from material characterization of weldment constituents,
ii. lack of detailed information about actual welding procedure,
iii. the amount of parameters that might influence WRS are too many,
iv. computer capacity limitations.

A consequence of these limitations is that a continuum mechanics approach is often preferable to use in welding simulations. Of importance is that this approach can result in sufficiently accurate WRS predictions.

The accuracy in predicting WRS is dependent of the influence of several parameters as mentioned above. Which of these parameters that are of most importance, and to what extent a parameter has to be considered in numerical simulations, is not obvious due to the complexity of the welding process. Regarding parameters related to material modelling of weldment constituents, their influence cannot be looked at isolated from other parameters since the influence of remaining parameters on WRS predictions is not fully understood [Mullins and Gunnars, 2012].

In the following, the impact of different parameters on the development of WRS during welding is investigated both from a physical perspective and from a perspective of numerical prediction of WRS. Focus is on circumferential welds in cylindric components and piping systems.

2.1. Geometry of weld and welded component

2.1.1. Physics

The geometry of the welded component influences WRS. Measures of importance for a butt weld in a pipe are the thickness of the pipe, t, mean radius of the pipe, R_m, the ratio R_m/t and the axial length of the pipe from the weld centreline, CL. Within the disturbance length $2.5\sqrt{R_m t}$ from CL, the degree of restraint for the pipe will influence the WRS. Beyond $2.5\sqrt{R_m t}$ from the CL, the degree of restraint is of less importance.

The ratio R_m/t is often used to define if the pipe is thin-walled, thick-walled or in between, see Table 2-1. The scale is sliding as there are no sharp transitions.

Table 2-1: Definition of a pipe based on the ratio R_m/t.

Type of pipe	R_m/t
Thin	>15
Intermediate	5 – 15
Thick	< 5

For thin-walled pipes, the axial WRS distribution is normally expected to be linear while for thick-walled pipes a sinusoidal distribution prevails [Bonnaud and Gunnars, 2016a]. It is however difficult to isolate the impact of R_m/t on WRS as other parameters influencing WRS also vary with t, R_m or R_m/t. The axial WRS distribution through the thickness of a butt-welded pipe can be taken as an example. Figure 2-2 illustrates the transition between linear and sinusoidal axial WRS distribution as a function of b/t and R_m/t where b is the height of the weld bead. Larger beads and larger inner radius (thin walled pipe) result in a more linear stress distribution whereas smaller beads and smaller inner radius (thick walled pipe) tend to result in a sinusoidal profile.

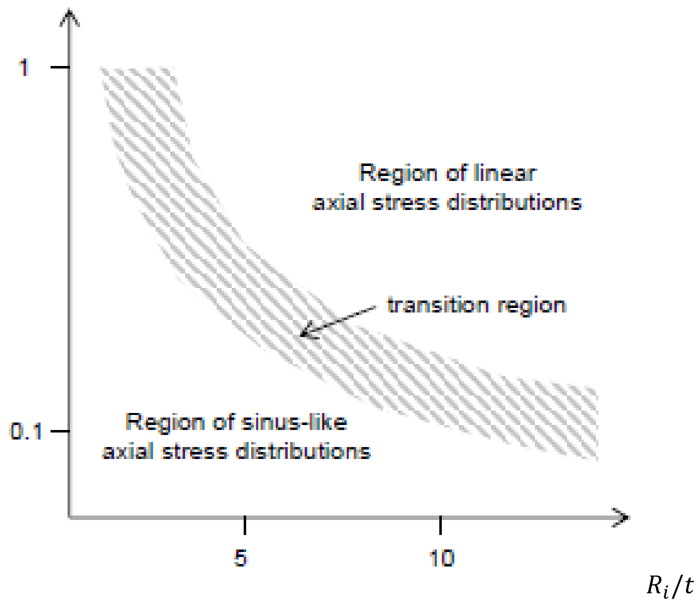

Figure 2-2: Sketch of regions for linear and sinusoidal stress distribution for axial stress in a pipe butt weld as a function of pipe geometry (R_i/t) and bead size (*b/t*) [Bonnaud and Gunnars, 2016a].

The main explanation for the linear axial stress distribution to occur is the development of radial shrinkage and associated axial bending at the weld when the pipe is thin and the size of beads are relatively large. The radial shrinkage of the pipe creates a bending moment over the thickness and thereby linearly distributed axial bending stresses. For thin-walled sections, these axial bending stresses dominate over the remaining axial stresses developed during welding.

For a thick-walled pipe the radial stiffness is higher. Hence, the radial shrinkage and associated axial bending will not be as developed as for the thin-walled pipe. The axial WRS developed in this pipe is more locally controlled resulting in a sinusoidal distribution.

The results in Figure 2-2 are valid provided that the length of welded pipes is sufficient and that they are free to move in the remote ends. For example, short pipes that are constrained in their remote ends would show different results. Shorter pipes would also mean a change in thermal conditions which can influence WRS.

The geometry of the weld influences the number of weld beads, the bead size and possible bead sequences. It influences the total volume of material subjected to large plastic straining as well as the local mechanical and thermal degree of constraint. This means that WRS depend on the weld geometry. Regarding the bead sequence, the location of the last weld bead has a large influence on the final residual stress distribution [Dong et al., 1998].

2.1.2. Simulation

From a phenomenologically point of view, the different stress distributions in Figure 2-2 can be captured in a simulation with an ordinary material model and proper modelling of boundary conditions. In order to predict the level of weld residual stresses however, a more complex and detailed material model is needed.

In order to predict WRS, representative geometry of the weld need to be considered in the welding simulation. This includes the bead size and the bead sequence.

2.2. Welding procedure

Parameters specified in the welding procedure include type and size of welded component, type and size of weld, type of welding process, bead size, bead sequence, heat input, preheat temperature, interpass temperature and post weld heat treatment (PWHT). These parameters can all have an impact on weld residual stresses.

2.2.1. Physics

Parameters given in the welding procedure specification (WPS) define the welding procedure. Weld residual stresses developed during welding are strongly dependent on these parameters. The heat input and the number of beads influence the melted zone and zone of high plastic strains for each bead. Recovery and recrystallization can both lower WRS. The effect of these mechanisms depends on the time-temperature profile at elevated temperature. The higher the temperature and the longer the time hold at this temperature, the more reduction of WRS. The impact of creep is similar. In multi-bead welds, consecutive passes can result in cyclic plastic hardening that in turn can result in increased WRS. Most of the parameters in the WPS influence the phenomena mentioned.

2.2.2. Simulation

Predicted weld residual stresses are strongly dependent on the welding parameters used in the simulation. In most cases, these parameters are based on the WPS. Of importance then is that the WPS corresponds to the actual welding situation. Where possible, additional information from the welding should be collected and, if needed, considered in the simulation. For a WPS covering large ranges of welds, test welds combined with measurements may be needed to determine a realistic heat input. If there are deviations between the WPS and the actual welding, it is crucial that this information is considered for a reliable WRS prediction. The sequence in which the beads are laid in an X-shaped girth weld, for example, influences WRS and welding deformation. The latter effect is discussed further in section 3-2.

2.3. Thermal boundary conditions

2.3.1. Physics

Since WRS essentially origin from misfit of local regions in the weldment caused by differences in thermal expansion and local thermal strains during welding, thermal boundary conditions are of importance for WRS. Thermal boundary conditions are controlled by type and size of welded component, type and size of weld, type of welding process, bead size, bead sequence, heat input, preheat temperature and interpass temperature.

2.3.2. Simulation

The thermal boundary conditions obviously differ between a 2D and a 3D model. In a 2D simulation, where each bead is instantaneously laid with no time dependent heat transfer in the circumferential direction, simplifications need to be introduced. In these simulations an approximate Rosenthal's solution is commonly used to describe heat input to 2D models. One way to assess if that an appropriate thermal degree of constraint is established (i.e. correct heat flow is assumed) is to analyse the peak temperature across the weldment during the simulation. Knowing that a certain microstructure is located say 2 mm from the fusion line and knowing that this microstructure corresponds to a certain peak temperature during the welding process, the heat flow in the simulation can be assessed. In a 3D simulation the thermal boundary conditions are directly given by the structure. Also here can the simulated peak temperature across the weldment during welding be used to verify the thermal modelling and analysis.

2.4. Mechanical degree of constraint

The mechanical degree of constraint during welding influences both weld residual stresses and welding deformation. In general, the more the pieces are constrained during welding, the higher the residual stresses get. On the other hand, if the pieces are free to move during welding, welding deformation is maximised.

2.4.1. Physics

The mechanical degree of constraint can be looked at from different perspectives, global and local. Welding two plates together with fixtures holding them in place during welding is an example of global constraint. A local constraint is given by the structure itself. Welding two pipes together is an example where the stiffness of the pipe itself, caused by its curvature, results in a local constraint at the weldment.

The mechanical degree of constraint can be difficult to determine. To completely constrain a component with fixtures is not practically possible. There will always be some movement of the structure. Mechanical degree of constraint controlled by the structure itself is more well-defined.

2.4.2. Simulation

In numerical prediction of WRS it is crucial that the mechanical degree of constraint during welding is well described. If the model is too constrained the simulated plastic hardening will be overestimated resulting in overestimated WRS. For a too low degree of constraint, the opposite prevails. The choice of 2D or 3D simulations is of importance in this context. In a 2D simulation of a girth weld, the mechanical degree of constraint is somewhat overestimated, particularly when the first beads are laid. The reason for this is that each bead in the simulation is laid instantaneously around the whole circumference. The analyst needs to be aware of this deficiency when performing a 2D welding simulation. In a 3D simulation of a girth weld it is possible to get the mechanical degree of constraint correct. A 3D simulation is however a lot more cost and time consuming. When the analyst decides which approach to choose (2D or 3D), the different advantages and drawbacks need to be evaluated from case to case.

2.5. Phase transformation

2.5.1. Physics

Phase transformations during the welding process can have significant influence on the final state of weld residual stresses. Especially volumetric expansion associated with the martensitic phase transformation in ferritic steels during rapid cooling can have a considerable impact. In martensitic phase transformation, volumetric expansion occurs because the atomic packing factor of ferrite is lower than that of austenite. If the expansion occurs at temperature close to the room temperature, a significant reduction in tensile residual stresses in the weld bead and locally in the HAZ can be achieved. The changes in the final state of the WRS due to the martensitic phase transformation are highly dependent on base/filler material chemical composition as well as on the transformation kinetics, which in turn are affected by the welding procedure, i.e. heat input characteristics [Hamelin et al., 2017] and weld inter-pass temperature. For austenitic steels, the effect of phase transformation on WRS can be neglected [Muransky et al., 2012].

2.5.2. Simulation

Implementation of phase transformation in welding simulations is a quite challenging and demanding work. The volumetric strains due to martensitic phase transformation (which are scarcely available) along with other strain components (elastic, plastic, thermal, creep) are to be incorporated into the material models used for welding simulations. One way of incorporating phase transformation is by modelling swelling using user subroutines. Another approach to implement phase transformation is by using a modified coefficient of thermal expansion in the welding simulation [Bhatti and Mångård, 2018]. This method can be used when the austenite-martensitic phase transformations in the ferritic steels have dominant influence on the residual stresses.

2.6. Differences in weldment constituent characteristics

2.6.1. Physics

Thermal and mechanical characteristics of weldment constituents often differ. With respect to yield strength, welds can be classified as under-matched, over-matched or matched. For an under-matched weld, the yield stress for the weld metal is lower than that for the parent material. For an over-matched weld the opposite prevails. Differences in properties for the weldment constituents influence the development of weld residual stresses during welding.

It is important to note that the as-welded properties of the filler material are influenced by hardening due to strain cycles that arise during the welding. When a bead has been laid and solidified, the weld material can be regarded to be in a non-hardened virgin state. Subsequent beads will cause cyclic plastic hardening to occur in previously laid beads. Thus, the material properties evolve from a virgin state to hardened state in a multi-bead weld. For the parent material, the preceding manufacturing process (besides the initial material properties) influences the material characteristics. Anisotropy and initial strains can for example influence WRS.

2.6.2. Simulations

In a welding simulation it is important that the material models used for the different weldment constituents well represent corresponding materials at start of welding. The material model used for the weld metal, for example, must be based on experimental results from testing of single weld beads with virgin properties. The reason why the weld material model cannot be based on test results from already finished multi-bead welds is that the material in these welds has been subjected to cyclic plastic hardening when the weld was made. In a welding simulation of a multi-bead weld, the cyclic plastic hardening in the weld region should result from the simulation itself. Regarding the parent material, introduced anisotropy or residual stresses from manufacturing might need to be considered in WRS predictions. One way to do this is to simulate the manufacturing process before the welding simulation is started.

Differences in thermal and mechanical characteristics between weldment constituents might require use of different types of constitutive models for the different constituents in a welding simulation. Welding simulation of a dissimilar weld with ferritic and austenitic steel would for example require consideration of phase transformation for the ferritic material. Other reasons for using different types of material models for the constituents might be different types of plastic hardening, varying properties due to microstructural evolution, different types of annealing or anisotropy.

2.7. Plastic hardening

2.7.1. Physics

During welding, the material in the weldment region is subjected to plastic deformation and thereby plastic hardening. Cyclic plastic hardening occurs in a bead when consecutive beads are laid. The number of beads in a weld normally increases with the thickness of the steel structure. Larger degree of cyclic plastic hardening can thus be expected in thicker structure welds. Consequently, the magnitude of WRS can be expected to be higher in multi-bead welds. In addition, the temperature is varying between ambient and melting temperature during welding. At higher temperatures, recovery, recrystallization and creep occur which influence the plastic hardening. Type of material, current WRS and the heat input characteristics during welding control their impact. Thus, the physics behind the plastic deformation response in a weldment during welding is very complex.

Strain controlled cyclic experiments in the plastic regime reveal that metals show isotropic, kinematic or mixed hardening. Type of hardening for a material might vary with temperature, for example mixed hardening at lower temperature and more isotropic hardening at higher. For mixed hardening materials (most of the steels are), it is often difficult to delineate the relative contributions of isotropic and kinematic hardening [Mullins and Gunnars, 2009].

2.7.2. Simulations

Many constitutive models describing plastic hardening in metals exist [Dahlberg and Segle, 2010]. Depending on application and available experimental data for the material to be described, a more or less detailed model can be applied. A general thumb of rule is to use an as simple model as possible, still capturing the physical phenomena of interest.

Influence of the plastic hardening model on distribution of WRS was investigated by use of 2D models in [Mullins and Gunnars, 2009]. The aim was to determine which material hardening model gave the best agreement with experimental results for stainless and nickel-based steels. Girth welded pipes with different geometry were studied. The investigation recommended the use of isotropic hardening models for use in welding simulations as this type of model gave the best overall agreement between predicted WRS and experimental measurements. A kinematic hardening model was not recommended as it consistently underestimated the magnitude of both axial and hoop stress. For pipes with larger R_i/t, the prediction with the isotropic hardening model was however not as good as for the other geometries. It was suggested that 2D axisymmetric welding simulations with higher R_i/t ratios might be mechanically overconstrained in the hoop direction due to the fact that the weld bead is effectively added instantaneously around the entire pipe circumference.

Plastic hardening is often divided into three main groups, i.e. isotropic, kinematic and mixed hardening. Assuming a circular yield surface, kinematic hardening means that the centre of the yield cylinder moves in the synoptic plane as plastic deformation occurs while the radius of the yield cylinder stays the same. Isotropic hardening, on the other hand, means that the centre of the yield cylinder stays at the centre of the synoptic plane while the radius of the yield cylinder increases during plastic deformation. Mixed hardening is a combination of isotropic and kinematic hardening. In general, welding simulation with an isotropic model results in higher WRS and lower accumulation of plastic strain. With a kinematic model the opposite prevails [Muránsky et al., 2012]. Not only the magnitude of residual stresses is influenced by the hardening model but also the distribution of WRS across the weld.

Plastic hardening can be linear or nonlinear. A linear model requires less experimental data than a nonlinear model when determining the constants of the model. If material ratcheting needs to be captured, nonlinear hardening has to be modelled. Structural ratcheting can be captured with both linear and nonlinear hardening models [Möller et al., 2015].

With respect to accumulation of ratchet strain during welding, it should be sufficient to capture structural ratcheting. The reason for this is that the characteristics of the loading situation in the weldment is deformation controlled [Möller et al., 2015]. In principle this means that linear hardening models can be used to predict ratcheting phenomena in welding simulations. However, nonlinear hardening models might, of other reasons than ratcheting, be needed to more accurately predict the plastic deformation response.

Loading can be proportional or non-proportional in a multi-axial stress space. Different materials respond differently on these two types of loading. Most material models used for welding simulations are based on the assumption that the loading is proportional. Constants in the models are determined based on results from testing with proportional loading. Material models based on the assumption of non-proportional loading would require both more complicated models and also more comprehensive experimental testing. It is judged that modelling of plastic hardening based on the assumption of proportional loading for most cases capture the plastic hardening evolution in the weldment during welding.

The choice of plastic hardening model for a material in a welding simulation should be independent of welding geometry. Nevertheless, there is still lack of evidence for a hardening model which is generally applicable for all welding geometries [Mullins and Gunnars, 2012]. If agreement between simulated and measured WRS requires different hardening models for different weld geometries, there should be other approximations in the welding simulation that explain the deviation. Use of a 2D instead of a 3D model, use of a too simplified annealing model or use of incorrect thermal or mechanical degrees of constraint are examples of parameters to investigate.

2.8. Distortion of yield surfaces

A circular von Mises yield surface is often assumed in plastic analyses. This assumption is in many cases sufficient for capturing plastic phenomena in steel materials. For some cases however, distortion of the yield surfaces needs to be considered.

2.8.1. Physics

Figure 2-3 shows subsequent yield surfaces during loading of an annealed ANSI 304 stainless steel tubular specimen [Wu and Yeh, 1991]. The arrow shows the loading direction giving the first point on the respective yield surface. Already the first subsequent yield surface indicates a distortion. The distortion increases with the number of subsequent yield surface.

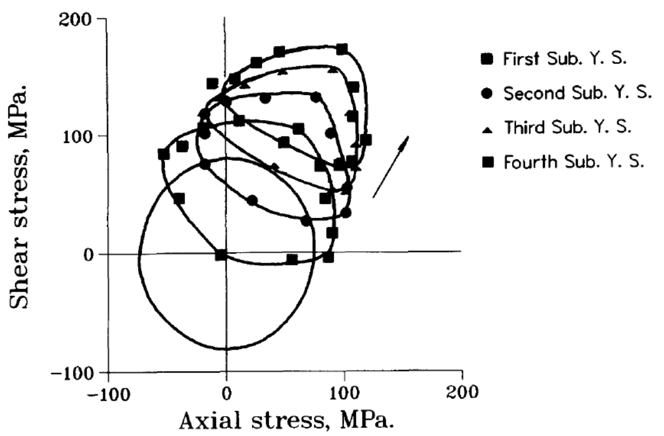

Figure 2-3: Subsequent yield surfaces during loading of an annealed ANSI type 304 stainless steel tubular specimen [Wu and Yeh, 1991].

The experiment, which result is shown in Figure 2-3, was conducted at ambient temperature. An increase of temperature is expected to influence the distortion.

2.8.2. Simulations

In most welding simulations, a von Mises yield surface is assumed. It is unclear how WRS would develop in a weldment where the material showed a characteristic like that in Figure 2-3. It is unknown to the authors if this has been investigated.

A constitutive model with a distorted yield surface is more complex than a von Mises model. The former model also requires more comprehensive experimental test data for determination of model constants. The temperature range of the welding process makes it further cumbersome to collect sufficient data for describing the distorted yield surface.

In the development of material models for welding simulations and improved WRS predictions, investigation of the impact of distorted yield surfaces might not be of highest priority. Other parameters are probably of more importance.

2.9. Limitation in experimental data

The amount of experimental data available for modelling will always be limited. This will restrict the complexity of material models used for prediction of WRS. A consequence of this situation is that the analyst has to assess which parameters and phenomena that are of most importance to capture in a welding simulation. This choice specifies type and characteristics of the constitutive models used.

2.10. Material anisotropy

2.10.1. Physics

The stress (and strain) state in weldments during welding is multiaxial. In general, the degree of multiaxiality increases with the thickness of the welded component and the degree of restraint. At surfaces, by definition, a biaxial stress state prevails. A multiaxial stress state in combination with material anisotropy complicates the plastic deformation response. Figure 2-4 shows stress-strain curves from uniaxial and multiaxial tensile testing of a 316L pipe material [Möller et al., 2015]. The uniaxial test was conducted in the axial direction of the pipe while the multiaxial test was conducted as an internal pressure test. Results show that the level of the pressure test curve was about 8 % lower than that of the uniaxial one. The deviation between the uniaxial and the multiaxial tests is assigned to mechanical anisotropy of the pipe material.

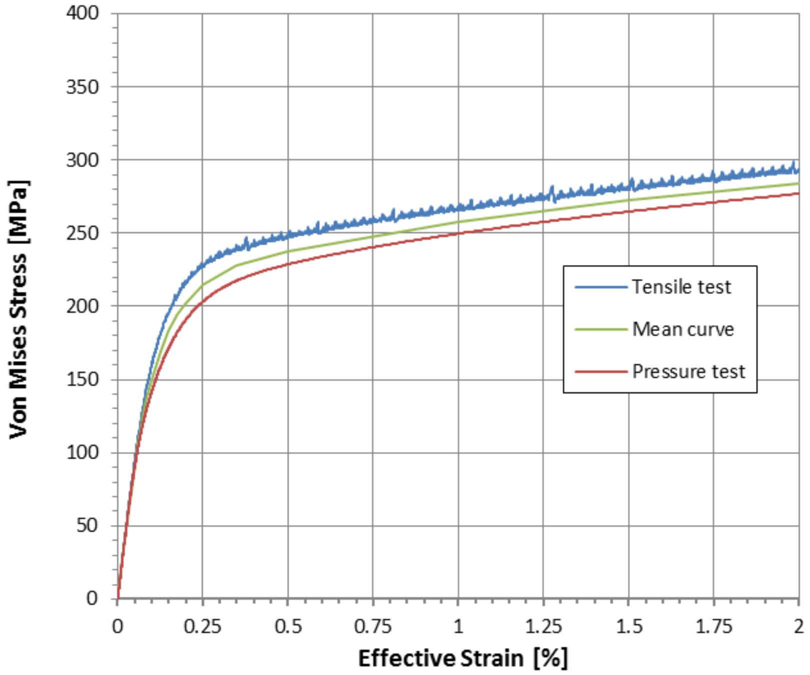

Figure 2-4: Experimental stress-strain curves from testing of a 316L pipe [Möller et al., 2015]. The uniaxial tensile test is conducted in the axial direction of pipe. In the multiaxial pressure test $\sigma_{\mathrm{hoop}} \approx 2\sigma_{\mathrm{ax}}$,

The manufacturing process of steel plates and pipes can cause its material to develop anisotropy. A subsequent welding in such material will result in a plastic deformation response that deviates from welding in corresponding isotropic material. Knowledge of the degree of anisotropy of the parent material is thus of importance for understanding the plastic deformation in the weldment region and thereby also for the understanding of how WRS are developed.

It can be expected that anisotropy prevails already in a single weld. The main reason being that the bead is given a geometric direction when it is laid. The material in a completed weld should thus also be anisotropic. The degree of anisotropy in welds and its impact on the plastic deformation response in the weldment region and its impact on WRS is not fully investigated or understood.

2.10.2. Simulations

In welding simulations, isotropic material models are commonly used where constants for the models are determined based on uniaxial test data. Parent material data is furthermore frequently used for corresponding weld material. As long as the parent material properties equal those of the weld metal and as long as the materials are isotropic, this approach may be an appropriate approximation. However, if the parent and/or the weld material exhibit substantial anisotropy, this might need to be considered in order to predict WRS sufficiently accurate.

Consideration of anisotropy in a numerical simulation can be done directly or indirectly. The direct approach uses an anisotropic material model. This approach requires a more comprehensive test program which might be very costly. The indirect approach uses isotropic material models where results from both uniaxial and multiaxial testing are used in determining the constants in the models. Contribution from multiaxial test data is motivated by the multiaxial stress state that prevails in the weldment during welding. The best way to do this has to be further investigated.

2.11. Mechanisms at elevated temperature

During welding the temperature is ranging from ambient to melting temperature. At lower temperatures, inelastic deformation occurs by plastic deformation. At elevated temperatures, additional mechanisms such as recovery, recrystallization and creep are present.

2.11.1. Physics

At elevated temperature the mechanisms plastic deformation, recovery, recrystallization and creep can all be present and thus influence the development of WRS. What these mechanisms have in common is their dependence of temperature and that the inelastic deformation they cause is related to movement of dislocations [Hull and Bacon, 1984]. What differs between them is the time scale they operate at. Plastic deformation occurs almost instantaneously as the stress exceeds yield stress while the other three mechanisms are more or less time dependent.

When a plastically deformed crystal is heated to moderate temperatures, recovery can occur. This mechanism is a result of pronounced softening of the dislocation hardened crystal. Recrystallization occurs if a cold worked metal is heated above a critical temperature. New grains relatively free from dislocations are then produced. Creep deformation is accumulated over time. This mechanism is associated with the longest time scale.

In an experiment with the stainless steels Type 304L, Alloy 600, Alloy 52 and Alloy 82, the effect of recovery and recrystallization was investigated [Yu et al., 2014]. Initial work hardening was reset by annealing the specimens at 1100 ºC for 1 hour followed by uniaxial straining to a true strain of about 0.2 (Y_p in Figure 2-5) at ambient temperature. After off-loading, the specimens were subjected to annealing at different temperatures (600 to 1150 ºC) for different periods of time (1 to 150 s). Finally, the yield stress (Y_p' in Figure 2-5) was determined at ambient temperature. Depending of the annealing procedure (temperature, time), the yield stress was more or less reduced, from Y_p to Y_p'.

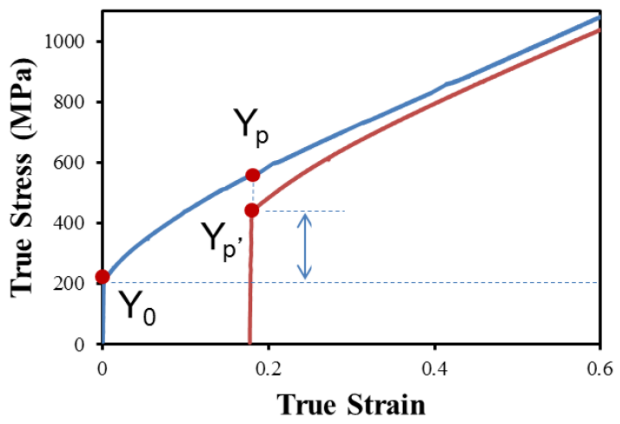

Figure 2-5: Reduction of yield stress for material subjected to different annealing temperature and exposure time [Yu et al., 2014].

In order to quantify the extent of softening caused by the annealing procedure, the following expression was suggested

$$R = \frac{Y_{\mathrm{p}} - Y_{p}'}{Y_{\mathrm{p}} - Y_{0}} \qquad (2\text{-}1)$$

where the yield stresses are defined in Figure 2-5. At lower annealing temperature and shorter annealing time, it was found that $Y_{\mathrm{p}} \approx Y_{\mathrm{p}}'$ (or $R \approx 0$) independent of material tested. As annealing temperature and annealing time were increased, R increased, particularly for Type 304L and Alloy 600. At a temperature of 1000 ^{o}C, R was almost equal to 1 for an annealing time of only 40 s for these two materials. At the lower temperatures, recovery dominated over recrystallization while at higher temperatures, the opposite prevailed.

2.11.2. Simulations

In general FE codes both creep and plastic deformation can be modelled as a function of temperature. Material models with different degree of complexity are available. The phenomena recovery and recrystallization are normally not possible to explicitly consider without using user subroutines. The FE code Abaqus has an annealing function which resets backstresses and the equivalent plastic strain in a material point as the temperature exceeds a predefined value. This procedure can be regarded as an implicit way of capturing the recovery and recrystallization mechanisms. This approach has a binary character which makes it somewhat coarse. One way to improve the annealing procedure in Abaqus is to use user subroutines. This was done for example in [Muránsky et al., 2011].

The fact that all four mechanisms plastic deformation, recovery, recrystallization and creep can be present at the same time at elevated temperature complicates the material modelling. The difficulty to separate the four mechanisms influence on results from elevated temperature experiments further complicates the modelling. In order to achieve a robust constitutive model that can be practically used in WRS simulations, simplifications are needed. Most convenient is to utilize the difference in time scale between the mechanisms. It is obvious that plastic deformation needs to be explicitly captured by the model as this mechanism is active over the whole temperature range, from ambient to melting temperature. In principle, the plastic deformation is an inelastic deformation that occurs almost instantaneously, i.e. at a very short time scale. The remaining three mechanisms recovery, recrystallization and creep all require a sufficient amount of time to occur.

Numerically, it is an advantage not to explicitly involve time when considering recovery, recrystallization and creep in a WRS simulation. An approach where only temperature controls these mechanisms simplifies both the material modelling and the analysis. Such an approach can be motivated as the cycle time at elevated temperature is relatively short and variations from bead to bead are moderate. Instead of explicitly consider the creep mechanism in the welding simulation, creep can be incorporated into the recovery and recrystallization mechanisms. With an extended annealing function, the three mechanisms recovery, recrystallization and creep can be simultaneously modelled in an effective and appropriate way [Muránsky et al., 2015]. The fact that the yield stress is substantially reduced at temperatures where the creep mechanism becomes active, i.e. plastic deformation is a strong competitor to creep at elevated temperature, further motivates the way to implicitly consider creep in welding simulations.

2.12. Complexity of constitutive models

In general, the higher the complexity of a constitutive model gets the more experimental data are needed for determining model constants. As welding is a process that takes place in a wide temperature range, from ambient to melting temperature, involving plastic deformation, creep and other phenomena, the test program quickly gets very comprehensive when the complexity of the material model increases. Practically, this means that the model complexity must be limited.

The analyst should strive for an as simple constitutive model as possible, still capturing phenomena of importance. Apart from problem with comprehensive material test programs, the risk of introducing errors when calibrating and using a very complex model is also a reason.

3. Effects of geometries and constraints

In this chapter some investigations on 2D welding simulations for pipes are presented with the purpose to point out some phenomena to be aware of when performing such analyses.

3.1. Extent of plastic deformation

In prediction of WRS by use of 2D models, the necessity to limit the number of DOFs is normally not an issue. A good habit, however, is to optimize the mesh in one or another way, especially for 3D simulations. Figure 3-1 shows the extension of the plastic zone l_{plastic} in a 2D welding simulation, measured from the centre of the girth weld. Within the plastic region of the pipe, the mesh must be sufficiently dense to capture the evolution of plastic deformation during the welding simulation.

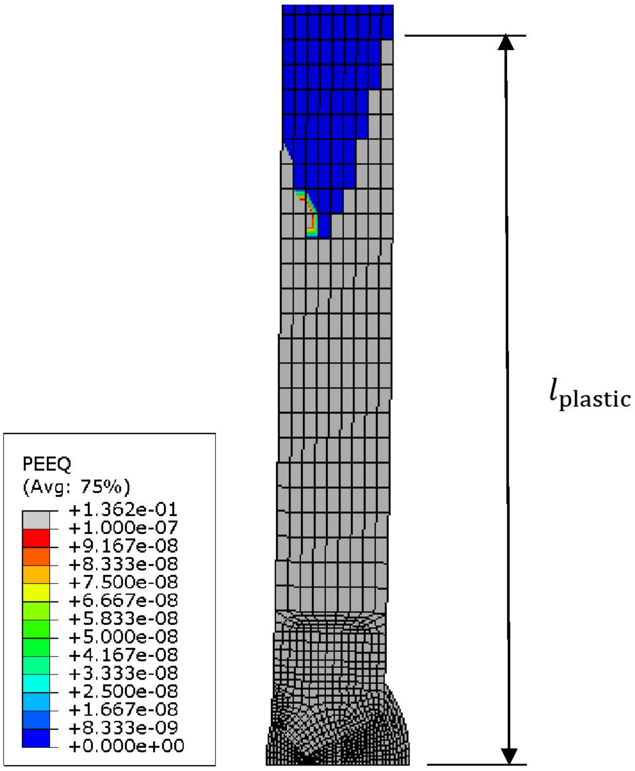

Figure 3-1: Equivalent plastic strain PEEQ in a pipe after a 2D welding simulation. l_{plastic} is the axial length of the pipe, measured from the centre of the X-shaped girth weld, in which plastic deformation occurs. Half of the weld is shown. Base and weld material is 316L. Mean radius of pipe R_m = 398 mm. Thickness of pipe t = 15.9 mm.

Table 3-1 summarises mean pipe radius R_{m}, pipe wall thickness t, bead height b, l_{plastic} and some measures of disturbance length for different pipe and weld geometries. The U-shaped girth welds have been analysed in [Bonnaud and Gunnars, 2016a]. For the constant value $R_m/t = 10.5$, the relative size of the plastic zone increases with increasing b/t. Beyond the distance l_{plastic} the pipe can be elastically modelled and the mesh can be coarser. The super element technique can also be used to model this elastic part of the structure without losing accuracy.

Table 3-1: Propagation of plastic deformation from the centre of a girth weld during a 2D welding simulation. R_m is the mean radius of the pipe, t is the thickness of the pipe wall and b is the bead height. l_{plastic} is defined in Figure 3-1. Base and weld material is 316L. Results for U-shaped welds are taken from [Bonnaud and Gunnars, 2016a].

Weld shape	R_m	t	R_m/t	b/t	$2.5\sqrt{R_m t}$	l_{plastic}	$l_{plastic}/t$	$\frac{l_{\text{plastic}}}{2.5\sqrt{R_m t}}$
	[mm]	[mm]	[-]	[-]	[mm]	[mm]	[-]	[-]
X	398	15.9	25	0.20	199	102	6.14	0.51
U	63	6	10.5	0.42	49	49	8.17	1
U	210	20	10.5	0.095	162	98	4.90	0.60
U	682.5	65	10.5	0.029	527	206	3.17	0.39

3.2. Bead sequence effects

Bead sequence influences both WRS and welding deformation in welded structures. An example is illustrated in Figure 3-2 for a double V girth weld with beads defined by numbers. Wall thickness and inner radius of pipe are 10 and 100 mm, respectively. The effect of shrinkage in hoop and axial direction was studied for this case [Bonnaud, 2017].

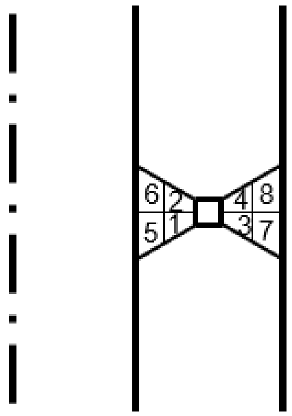

Figure 3-2: Weld beads defined by numbers for a double V girth weld. Wall thickness of pipe $t = 10$ mm and inner radius $R_i = 100$ mm.

Figure 3-3 illustrates that shrinkage in the hoop direction results in a radial displacement which reduces the pipe radius, independent of where the laid bead is located. Shrinkage in the axial direction can result in a radial displacement that either decreases or increases the pipe radius. If the location of the laid bead is located outside the mid-surface of the pipe wall, the radius will decrease. If the laid bead is located inside the mid-surface of the pipe wall, the opposite prevails, see Figure 3-3.

For beads laid outside the mid-surface of the pipe wall, both hoop and axial shrinkage will contribute to a decrease of the pipe radius. For beads laid inside the mid-surface of the pipe wall, the radial displacement contribution from the hoop and the axial shrinkage will counteract each other, see Figure 3-3.

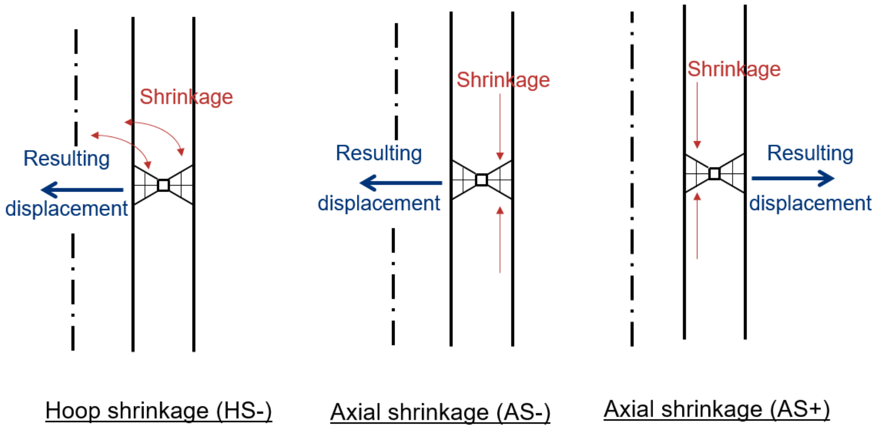

Figure 3-3: Resulting radial displacement as a result of hoop or axial shrinkage.

Figure 3-4 shows predicted radial displacement of the inner surface of the pipe at the weld centre during welding for two different bead sequences, i.e. 1-2-5-6-3-4-7-8 and 3-4-7-8-1-2-5-6. Independent of bead sequence, the radius of the pipe decreases. The first bead sequence will however result in more radial displacement than the second. Figure 3-4 also shows that the radial displacement caused by shrinkage when the beads 1-2-5-6 are laid depends on when in the sequence these beads are laid. For the bead sequence 1-2-5-6-3-4-7-8, hoop shrinkage dominates over axial shrinkage and the pipe radius decreases. For the bead sequence 3-4-7-8-1-2-5-6, axial shrinkage dominates over hoop shrinkage resulting in an increased pipe radius when beads 1-2-5-6 are laid.

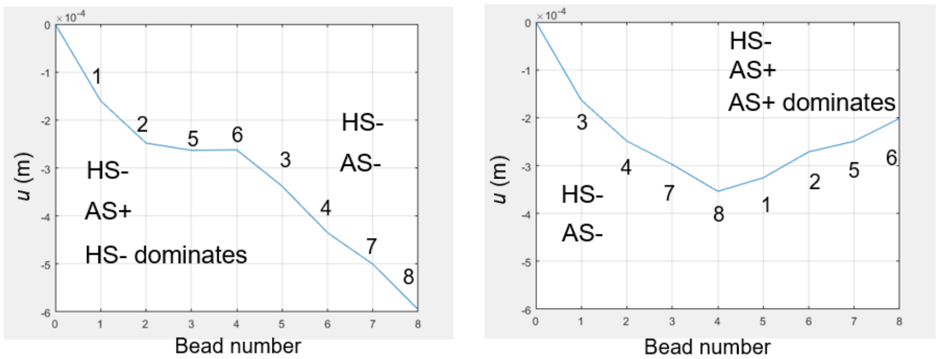

Figure 3-4: Radial displacement of inner surface of pipe at a double V weld as a function of bead sequence. Left figure shows radial displacement for bead sequence 1-2-5-6-3-4-7-8. Right figure shows radial displacement for bead sequence 3-4-7-8-1-2-5-6.

This example demonstrates that the bead sequence is essential for welding deformations. It is obvious that also residual stresses are influenced by the bead sequence. In this context the importance of following the welding procedure specification (WPS) during welding should be pointed out. The WPS is important for predictions of WRS and welding deformation, and a deviation from the WPS could give incorrect predictions. Known deviations from the WPS during welding should be taken into account in welding simulations.

3.3. Stress and strain evolution in a bead

This section illustrates the complexity of the evolution of stresses and strains during welding. Figure 3-5 shows a U-shaped girth weld with seven beads that is studied numerically by use of a 2D model. Pipe thickness is $t = 8$ mm and inner radius is $R_i = 80$. Length of pipe on each side of the weld centre is 400 mm. Remote pipe ends are free to move during welding. Both parent and filler material is stainless steel 316L with mixed plastic hardening. An annealing function is activated in the simulation at $T = 1000$ ºC which resets backstresses and equivalent plastic strain to zero. Bead number 3 is investigated as all beads in the weld are deposited.

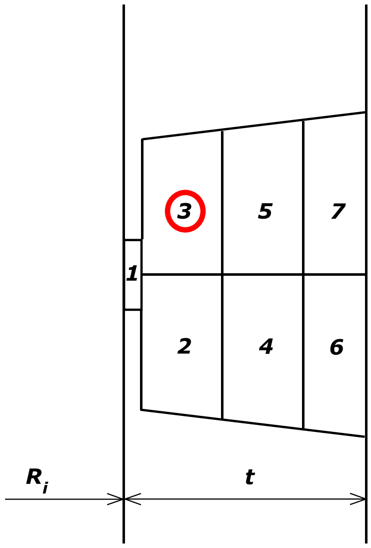

Figure 3-5: U-shaped girth weld with bead sequence 1 to 7. Stress and strain evolution in the centre of bead 3 is investigated.

Figure 3-6 shows radial, axial and hoop stress in the centre of bead 3 as the seven beads are deposited. Stresses start to develop in bead 3 first when bead 3 is laid. The radial stress is generally low in the weld and not further discussed.

Compressive axial stresses are developed in bead 3 as bead 3 has been deposited. The main reason is the radial shrinkage of bead 3 during cooling which results in axial bending stresses over the section with tension stresses at the inside of the pipe and compressive stresses in bead 3. After bead 4 has been laid, the axial stress in bead 3 increases but remains compressive. The axial stress in bead 3 shift to tensile when bead 5 is laid. As bead 5 and the rest of the structure cools down, shrinkage of the weld results in enhanced axial bending stresses in the weld section. Now, as bead 5 is located outside bead 3, positive bending stresses are developed in bead 3, see Figure 3-6. When bead 5 is laid, the temperature in bead 3 exceeds 1000 ºC. The resulting annealing in bead 3 further accelerates the shift to tensile as the cyclic plastic hardening is reset (backstresses and equivalent plastic strain are reset to zero, see Figure 3-9). Annealing in bead 3 does not occur when bead 6 and 7 are laid. The axial stress and the axial plastic strain in bead 3 vary somewhat when the final two beads are laid, see Figure 3-6 and 3-7.

The hoop stress in bead 3 shows an initial peak as bead 3 is laid, see Figure 3-6. The explanation is the radial expansion of the surrounding material (bead 1, bead 2 and parent material the vicinity of bead 3) when the temperature increases in this region at the same time as the temperature of bead 3 starts to decrease. During this initial stage, plastic strain in the hoop direction increases in bead 3, see Figure 3-8. When the temperature reaches room temperature the hoop stress is around 40 MPa.

Just before bead 4 is laid, the surrounding material to bead 4 is heated up. This pre-heating is an effect of the imitation of the moving electric arch around the circumference in the 2D simulation. Now, as bead 3 is heated up, the surrounding parent material to bead 3 restrains it to expand radially which results in compressive hoop stresses, see Figure 3-6. At the same time plastic hoop strains are reduced, see Figure 3-8. The plastic axial strain increases at the same time in bead 3. This is a result of the radial expansion of bead 2 as this bead is more heated up than bead 3. When bead 4 has been deposited, the plastic hoop strains increase again in bead 3. Thus, bead 3 is contracting more in the hoop and radial direction than its surrounding material during cooling. The axial plastic strain in bead 3 is reduced after bead 4 has been laid caused by radial shrinkage and compressive bending stresses. Annealing in bead 2 which resets cyclic plastic hardening in bead 2 also has an impact on the stress and the strain field in bead 3.

Just before and during bead 5 is laid, the temperature in bead 3 exceeds the annealing temperature 1000 ºC and its cyclic plastic hardening is reset. From now on, the initial high stresses that were seen when bead 3 and 4 were laid vanishes. (If annealing is not considered in the analysis, the initial high hoop stress would remain also when bead 5, 6 and 7 are laid.) The reduction in axial plastic strain in bead 3 when bead 5 is laid could be explained by the larger axial contraction in bead 5 than in bead 3 during cooling, see Figure 3-7. The hoop stress and the plastic hoop strain will continuously increase and decrease, respectively, as bead 6 and 7 are laid. The axial stress and axial plastic strain also vary as bead 6 and 7 are laid.

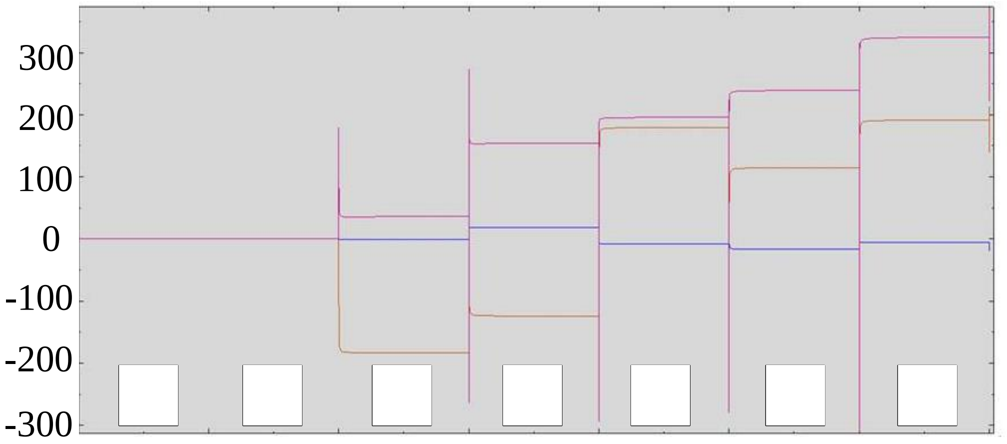

Figure 3-6: Radial ($S_{11}, blue$), axial ($S_{22}, orange$) and hoop (S_{33}, red) stress in centre of bead 3 as a function of bead deposited. Number of bead laid is shown in white squares. Stress is given in MPa.

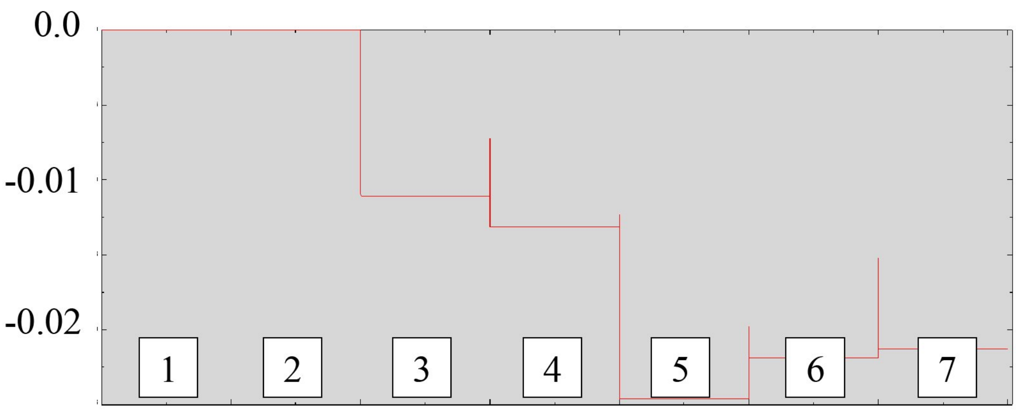

Figure 3-7: Plastic strain in axial direction in centre in bead 3 as a function of bead deposited. Number of bead laid is shown in white squares.

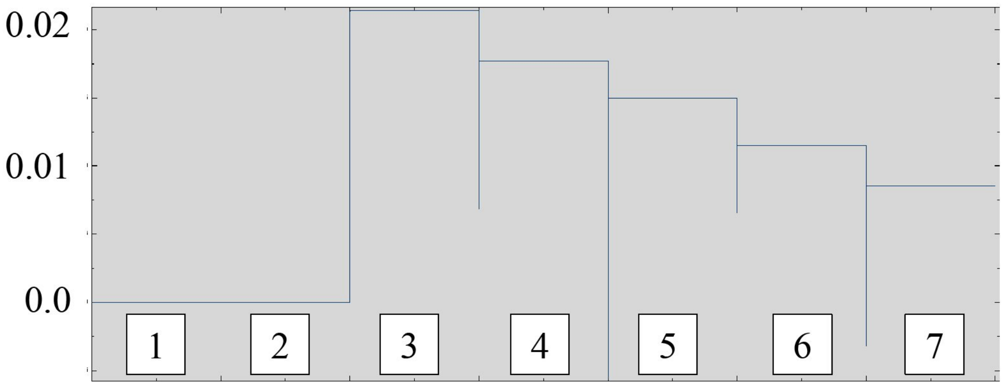

Figure 3-8: Plastic strain in hoop direction in centre of bead 3 as a function of bead deposited. Number of bead laid is shown in white squares.

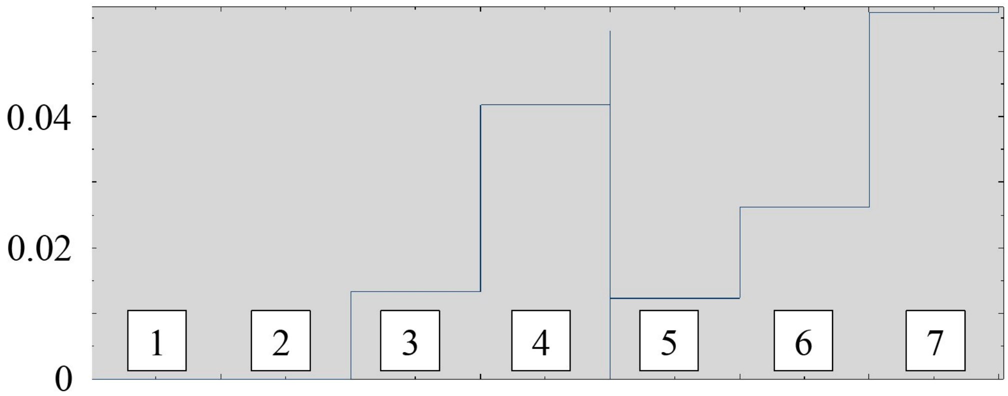

Figure 3-9: Equivalent plastic strain in centre of bead 3 as a function of bead deposited. Number of bead laid is shown in white squares.

This example shows the complexity of how stress and strain evolve in a weld bead during welding. It also shows the necessity of numerical simulations to understand the processes involved during welding.

3.4. Effect of thermal and mechanical constraint

The thermal and mechanical degree of constraint influence the stress and strain evolution in a weld during welding. The same U-shaped girth weld as in section 3.3 is investigated by use of a 2D model, see Figure 3-5. The pipe thickness $t = 8$ mm is kept constant. Two different global geometries R_i/t are analysed; $R_i/t = 10$ and $R_i/t = 1$, corresponding to a thin-walled and a thick-walled pipe with respect to global deformation. The same heat input characteristics is applied for the two cases. The stress field at room temperature after bead 2 and bead 3 have been laid is studied.

Figure 3-10 shows the axial stress S_{22} after bead 2 has been laid. The difference in deformation between the two cases reveals the difference in mechanical degree of constraint. The bending stress is 46% higher in the thin-walled pipe ($R_i/t = 10$) compared to the thick-walled ($R_i/t = 1$). Corresponding difference in the hoop direction is 16%, see Figure 3-11. The effect of the degree of mechanical constraint is large, particularly on the axial stresses.

Figure 3-12 shows the axial stress S_{22} after bead 3 has been laid. The difference in deformation between the two cases is still large. The bending stress is 44% higher in the thin-walled pipe compared to the thick-walled. Corresponding difference in the hoop direction is 25%, see Figure 3-13.

The difference in mechanical degree of constraint results in a large difference in stresses. How well these predicted stresses correspond to the real situation is not completely clear. The 2D model is a simplification that cannot fully capture the mechanical degree of constraint during the welding around the circumference. Particularly when the first beads are laid, and if the pipe is thin-walled, the 2D model deviates from the local deformation and constraint in the real welding situation. In addition, the heat input characteristics is the same for the two cases in the 2D simulations. This simplification does not account for the potential difference in cooling rate for the two cases.

In order to further understand how thermal and mechanical degree of constraint should be taken into account in 2D predictions of WRS, 3D welding simulations are needed. As several complex phenomena are involved in welding, the number of uncertainties need to be reduced when possible. By use of 3D models in prediction of WRS, thermal and mechanical degree of constraint can be modelled in a correct way and their impact better understood. With this knowledge, potential remedies for the deficiencies with 2D simulations can be found.

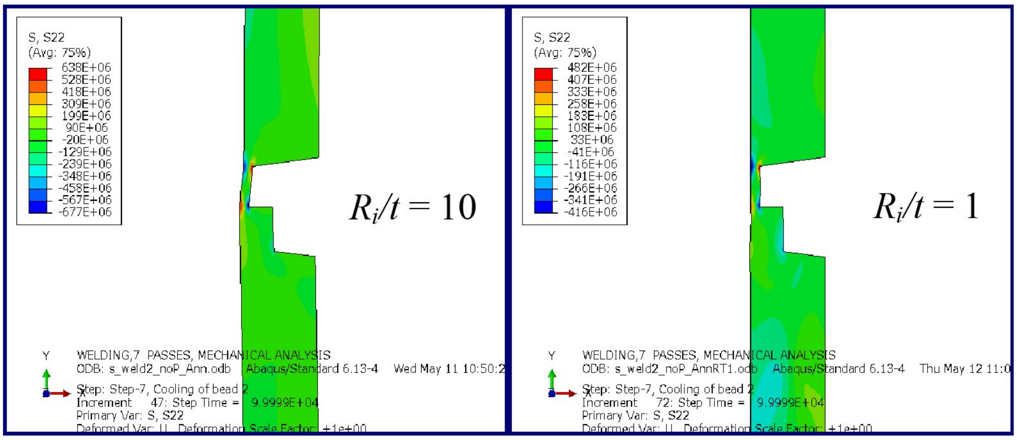

Figure 3-10: Axial stress S_{22} in Pa at room temperature after bead two has been laid. Left figure: $R_i/t = 10$. Right figure: $R_i/t = 1$. Deformation scale factor is 1.

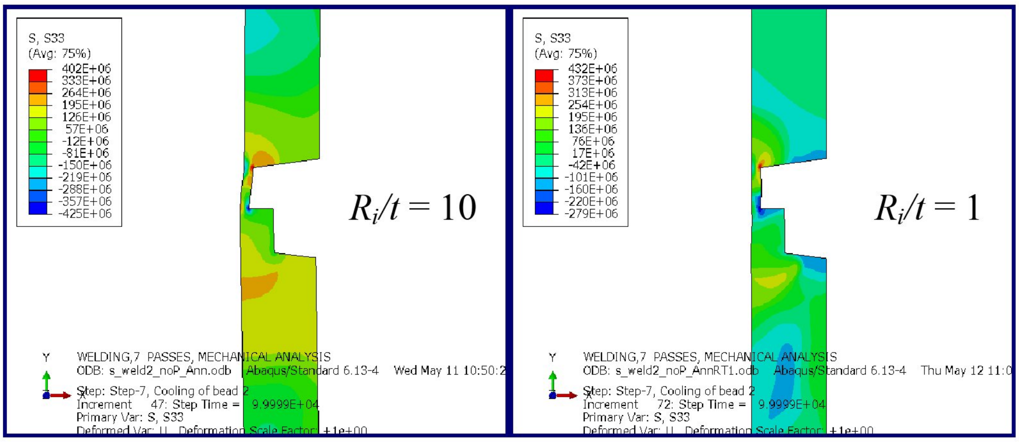

Figure 3-11: Hoop stress S_{33} in Pa at room temperature after bead two has been laid. Left figure: $R_i/t = 10$. Right figure: $R_i/t = 1$. Deformation scale factor is 1.

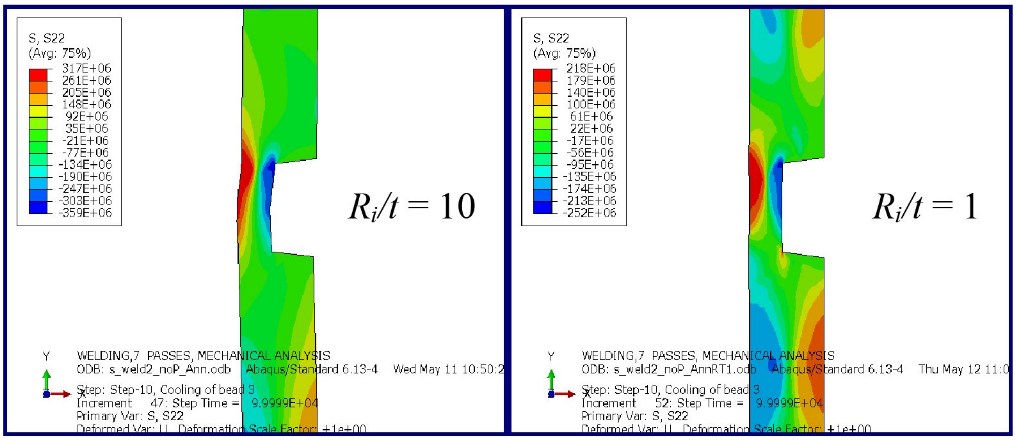

Figure 3-12: Axial stress S_{22} in Pa at room temperature after bead three has been laid. Left figure: $R_i/t = 10$. Right figure: $R_i/t = 1$. Deformation scale factor is 1.

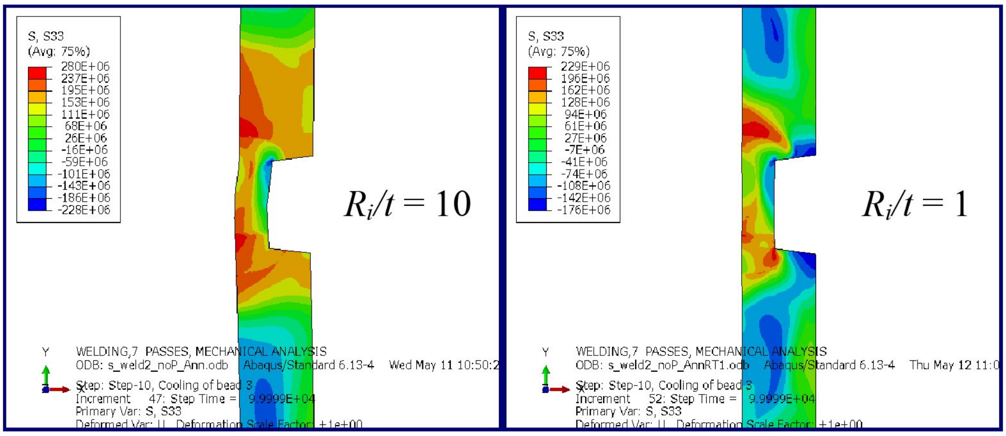

Figure 3-13: Hoop stress S_{33} in Pa at room temperature after bead three has been laid. Left figure: $R_i/t = 10$. Right figure: $R_i/t = 1$. Deformation scale factor is 1.

4. Discussions

Many mechanisms and phenomena are involved in welding. Some of these are more important than others for how WRS develop. In chapter two of this report, a number of parameters influencing WRS are described and discussed from a physical and a simulation perspective. The parameters interact with each other making the welding process very complex with respect to prediction of residual stresses. If anisotropy, distorted yield surfaces, cyclic softening or cyclic hardening, recovery, recrystallization, creep, and phase transformation would have to be explicitly considered, modelling of the weldment constituent materials would be extremely complex. Simplifications in prediction of WRS are needed. The question is, in comparison to welding simulations of today, which mechanisms and phenomena need to be considered in more detail for improved accuracy in WRS predictions. This question needs to be answered in parallel with further development of constitutive material models for use in welding simulations.

4.1. Plastic deformation

WRS are a result of misfit of deformation in local regions in the weldment during welding. Thermal expansion and contraction in a structure with constraints cause inelastic deformation to occur which after cooling, together with the effect of differences in thermal expansion coefficient between weldment constituents, result in elastic strains and thereby WRS. As plastic deformation occurs in the weld over the whole temperature range, this mechanism is expected to be one of the most important to capture in a welding simulation. As a minimum, the material models should describe type of plastic hardening and cyclic plastic hardening in detail for the relevant temperature and strain ranges.

It is expected that plastic hardening for almost all steel materials is mixed isotropic and kinematic. For specific geometries and materials, it might be that better predictions of measured WRS can be achieved with pure isotropic or pure kinematic hardening models than with mixed models. This agreement should not be attributed to the material model without a deeper investigation. Even though mixed models best describe the weldment constituent materials, simplifications and approximations done in a welding simulation might favour more simple material models. With an improved welding simulation with less simplifications and approximations, the mixed hardening model might again give the best prediction. Taking welding simulations with an isotropic hardening model as an example, selection of an appropriate annealing temperature could result in good agreement between predicted and measured WRS. This way of tuning can work out for one specific geometry but as the geometry changes the prediction will lose in accuracy.

4.2. Mechanisms at elevated temperature

At elevated temperature essentially four mechanisms are of importance, i.e. plastic deformation, recovery, recrystallization and creep. All mechanisms involve movement of dislocations and are dependent on temperature. One difference between them is the time scale they operate at. Plastic deformation occurs almost instantaneously while the other three require time to become active. Material models describing creep as a function of time and temperature are available in general finite element codes. Explicit models for recovery and recrystallization are not commonly available. The possibility to combine the mechanisms plastic deformation, recovery, recrystallization and creep in a single model in a temperature range from room to melting temperature is almost impossible without simplifications.

One simplistic way to take account for recovery, recrystallization and creep in a welding simulation is to introduce an annealing function that relaxes stresses at elevated temperature. The controlling parameters time and temperature are here reduced to temperature only. This approach might be appropriate as the cycle time at elevated temperature, when a bead is laid, is relatively short with moderate variations from bead to bead. One advantage with such an approach is that it is relatively easy to implement it into FE codes. By controlling plastic hardening measures at elevated temperature (normally backstresses and equivalent plastic strain), recovery, recrystallization and creep can be considered through an annealing function.

4.3. Thermal and mechanical degree of constraint

Use of correct thermal and mechanical degree of constraint in welding simulations are essential for accurate predictions of WRS. In principle, correct conditions corresponding to the real welding situation can be established with a 3D model. The size of the 3D model is the only limitation for the analysis. With 2D models, welding simulations can be done more efficiently. However, these models imply simplifications regarding thermal and mechanical constraints.

In a 2D welding simulation of a girth weld, thermal heat is applied instantaneously around the whole circumference when a bead is laid. In order to simulate the reality, approximations are needed. Preheat of the already laid beads is applied in a simplified way when a new bead is laid. The relation between reached peak temperature and microstructure in the weldment can be used to calibrate the heat input as a function of time in the simulation. Regarding the mechanical degree of constraint, the 2D model results in deviation from the reality as each circumferential bead is laid instantaneously in the simulation. The approximations regarding the thermal and mechanical degree of constraint in a 2D model is probably one important explanation why the same plastic hardening model has not been possible to use for accurate prediction of WRS in girth welds independent of pipe thickness [Mullins and Gunnars, 2012].

To further understand the limitations with 2D welding simulations and how these simulations can be improved with respect to thermal and mechanical degree of constraint, it is necessary to investigate and compare results from both 2D and 3D welding simulations [Bonnaud and Gunnars, 2016b].

4.4. Anisotropy and distorted yield surfaces

Anisotropy and distorted yield surfaces are normally not considered in welding simulations. The simple answer for this is probably that it would make it a lot more complicated, both from an experimental and a modelling perspective, to consider these phenomena. The potential impact of anisotropy and distorted yield surfaces on WRS is not fully understood. An investigation of how these phenomena influence WRS is therefore of interest. Depending of the outcome, these phenomena might have to be considered in the constitutive models.

Reliable experimental results from testing of parent material, single beads and complete welds should form basis for an investigation of the impact of firstly anisotropy and secondly distorted yield surfaces on WRS. Welding should be done in accordance with detailed welding procedures. Experimental data should be input to subsequent material modelling and welding simulations.

4.5. Accurate experimental measurements

It cannot be enough emphasised how important it is to establish reliable experimental data. Both testing of properties for separate weldment constituents (parent material, single beads, complete welds) as well as reliable measurements of residual stresses for well-defined weldments are needed [Hamelin et al., 2017]. Without these results, it is not possible to further develop constitutive models for improved prediction of WRS.

Experimental investigation of all phenomena and parameters described in chapter two would require a very comprehensive testing. When possible, argument should be found to limit the number of investigated parameters.

5. Conclusions

The physics of welding is very complex. Many mechanisms and phenomena influence the development of WRS during welding. It is not completely clear which of them that is of most importance and which of them that has a minor impact.

In prediction of WRS, the constitutive material models used are essential. For accurate predictions, the models must be able to sufficiently well describe the material response of the weldment constituents. Selection of a material model should only depend on the material behaviour and not on other parameters, mechanisms or modelling techniques. For example, accurate WRS predictions for a weld should not require different material models if the simulation is done in 2D or 3D. Thus, before constitutive models for welding simulations can be further developed, the interaction between all essential mechanisms and phenomena influencing WRS, and their respective impact on WRS, must be understood.

In this report, mechanisms and phenomena related to welding and WRS are investigated. Focus is on both physics and simulation. The purpose is to understand which mechanisms and phenomena that need to be considered for reliable predictions of WRS and how this knowledge should be taken into account in the material modelling. Some mechanisms are pointed out for further investigation, i.e. annealing (recovery, recrystallization, creep), thermal and mechanical degree of constraint (2D vs 3D simulations), phase transformation and anisotropy. Suggested work involves experimental activities, constitutive material modelling and numerical predictions of WRS.

6. Further work

The following work is suggested:

1. Establishment of reliable experimental data from testing of properties for separate weldment constituents (parent material, single beads, complete welds) as well as reliable measurements of residual stresses from well-defined weldments. Properties tested depends on phenomenon investigated. The weldment constituents should correspond to the well-defined weldment.

2. The elevated temperature mechanisms recovery, recrystallization and creep should be modelled by use of an improved annealing function. A binary function where full annealing occurs when the temperature exceeds a predefined temperature is not sufficient. Instead should annealing occur within a temperature span. Experimental data at elevated temperature form basis for the development.

3. Thermal and mechanical degree of constraint and their impact on prediction of WRS in 2D welding simulations should be investigated. To further understand the limitations with 2D welding simulations and how these simulations can be improved, it is necessary to investigate and compare results from 2D and 3D welding simulations. Well established measurements of the temperature field evolution and measurements of residual stresses from well controlled welding experiments form basis for this work.

4. Consideration of anisotropy in welding simulations should be investigated both from an experimental and a numerical perspective. Well defined and limited experiments should form basis. Parent material with known anisotropy from manufacturing is investigated experimentally as well as anisotropy in single beads and in complete welds. Constitutive material models considering anisotropy are investigated and evaluated. Accurate measurements of residual stress from well controlled welding experiments are important for validation of material modelling and welding simulations.

5. Appropriate ways to improve implementation of phase transformation into constitutive models in general FE codes for welding simulations with ferritic steels should be investigated.

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