

Welding Sequence Definition Using Numerical Calculation

Three calculations were made with different welding sequences and clamping conditions to predict distortion after pipe welding

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ABSTRACT

The welding simulation for a pipe in a hydropower plant was made due to very large dimensions. The pipe is 5.5 m in diameter. The main aim was to predict the welding sequence that will cause no deformation after welding because machining the pipe at the construction site is almost impossible. For achieving distortion in the desirable limits, the welding process was simulated with the finite element program Sysweld. The macro weld deposit methodology was used to minimize the calculation time. Two different finite element models (FEM) were made. Three different welding sequences and clamping conditions were calculated to reduce distortion. The calculation of microstructure constituents in the virtual complex geometry of joints was also analyzed.

Introduction

Welding is an important process and has a very important part in industry, especially in the automotive, maritime, and energy sectors. Although welding has many advantages, it also has some disadvantages such as thermal expansion and shrinkage or microstructural transformations, which cause stresses. All these processes have a main influence on the distortion during and after welding. With knowing all these properties and welding parameters, it's possible to predict the final distortion. Accurate prediction of the distortion is important when distortion on some unique, large parts has to be predicted. To achieve the deformation in the desirable limits, changes in welding parameters can be made, such as welding sequence and clamping of the welded parts. When changing some welding parameters of complex parts, with a large number of beads or multipass welding, etc., it's not easy to predict the distortion after welding (Refs. 1, 2).

When the welding procedure is planned, it's now possible to predict the distortion with numerical calculation. Distortion and residual stresses with plastic history of welded components can be cal-

culated with numerical simulation, taking into account all relevant physical phenomena. Therefore, planning or making the optimization can be done virtually, and when results are acceptable, the transfer of new technology in practice can be made with minimum prototyping.

Designing the welding fabrication with the computer to minimize or control distortion can significantly reduce fabrication costs. Controlling residual stress can significantly enhance the structure's service life.

With proper modeling, considering the distortion, elimination of expensive distortion corrections can be done; the reduction of machining requirements can be made; the minimization of capital equipment cost can be expected; quality improvements can be made; and premachining concepts can be used. Modeling — considering residual stress control has influence on weight reducing and maximization of fatigue performance — can lead to quality enhancements and minimize cost of service problems (Ref. 3).

For getting all these data with numerical calculation, the consideration of all main physical effects, which accrues at welding, has to be taken into account. This numerical calculation is based on coupled thermo-metallurgical analysis. All results are calculated with a modified heat convection, shown in Equation 1.

With this equation, it's possible to perform nonlinear computations with all material properties depending on temperature, phase and material transformations, proportion of chemical elements, and other auxiliary variables. The calculation of nonlinear heat transfer, nonlinear geometry, including large strains, isotropic and kinematic strain hardening including phase transformations, transformation plasticity, and nonlinear mixture rules for the yield stress of phases can be done (Refs. 4–6).

$$\left(\sum_i P_i (\rho C)_i \right) \frac{\partial T}{\partial t} - \nabla \cdot \left(\left(\sum_i P_i \lambda_i \right) \nabla T \right) + \sum_{i < j} L_{ij}(T) A_{ij} = Q \quad (1)$$

P	phase proportion
T	temperature
t	time
i, j	phases
ρ	mass density
C	specific heat
λ	thermal conductivity
Q	heat sources
$L_{ij}(T)$	latent heat of $i \rightarrow j$ transformation
A_{ij}	proportion of phase i transformed to j in time unit

Numerical simulation was used for the prediction of final distortion after welding a pipe and flange for a hydropower plant. The welded construction is shown in Fig. 1. The pipe's diameter is 5.5 m, and the flange is 140 mm thick. Making the pipe and flange is not the issue in this paper. The pipe and flange were welded and then machined in the workshop to the desirable dimensions. The problem occurred due to the transport reasons. The pipe will be used in a reversible hydropower plant whose location is high in

KEYWORDS

Pipe
Hydropower Plant
Welding Sequences
Clamping Conditions
Macro Bead Deposit
Methodology (MBD)
Finite Element Models (FEM)

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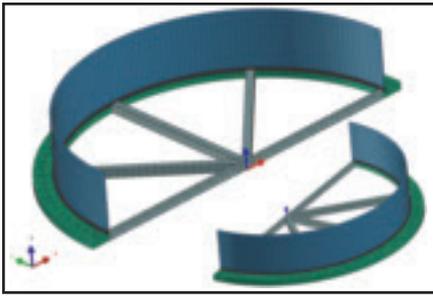


Fig. 1 — The FEM mesh of a pipe and flange.

Table 1 — Welding Parameters

Electrode	EVB 50
Current type/polarity	DC/+
Electrode size	3.25/4
Current	110–130/140–160 A
Voltage	24–26/25–27 V
Welding speed	20–25/25–30 cm/min

the Alps, about 2000 m above sea level. The transport of 5.5-m pipe by the road is not possible because the tunnels are too small. Transporting the already welded pipe and flange together by helicopter is not possible because the pipe with flange is too heavy for transport by a helicopter at 2000 m above sea level. Therefore, the pipe and flange are to be transported separately by a helicopter to the hydropower plant location.

The aim of the numerical calculation was to predict the distortion after welding and to determine the welding sequence of the welding to have the distortion in the tolerance, so the welding will be done without machining after welding. The heat input was defined with macro bead deposit methodology (MBD). This method is convenient for calculating very large structures, where the main aim is deformation (Ref. 4).

Preparing the FEM Mesh for Calculation

For this calculation, two different finite element models (FEM) were made. The finite element mesh for the calculation is shown in Fig. 1. Only half of the model is meshed because the symmetry was taken into account. The model has 46237 elements.

Three simulations with different welding sequences and clamping conditions were made. The sequence and FEM for the first and second calculations are shown in Fig. 2A. Welding started on the inner side of the pipe with six beads and continued with the rest ten beads on the outer side of the pipe. The difference between the first and second sequence was in clamping and preheating. For the first calculation, the profiles for reinforcement and obtaining the round shape that are seen in Fig. 1 were not then into account, and the preheating was not defined. In the

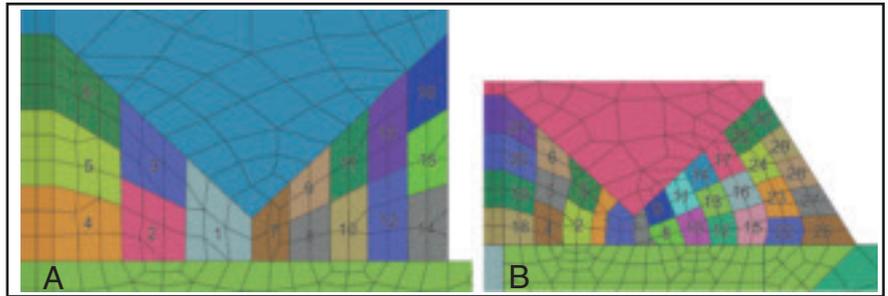


Fig. 2 — A — Welding sequence and mesh for the first and second calculation; B — welding sequence and mesh for the third calculation.

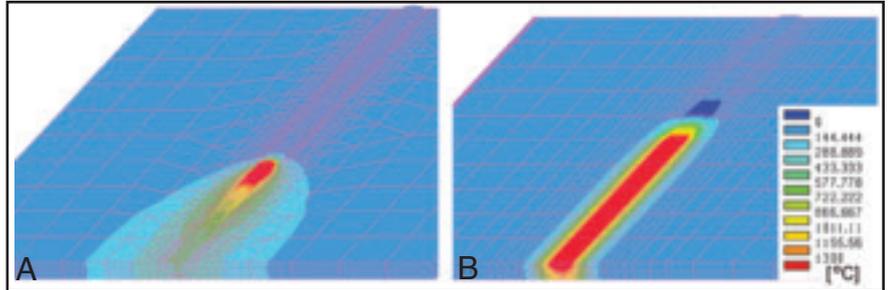


Fig. 3 — Temperature distribution for the third bead of a butt joint. A — Transient method; B — MBD method.

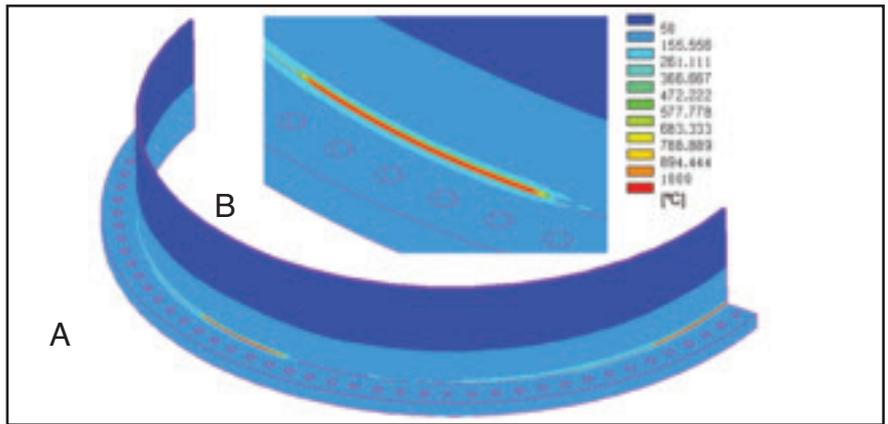


Fig. 4 — Temperature distribution while welding the last bead with the first sequence.

second calculation, the welding sequence was not changed; only the reinforcement was taken into account, and the preheating was 150°C.

For the third calculation, the sequence and mesh were changed. Welding started on the inner side of the pipe with six beads; welding continued with eleven beads on the outer side of the pipe. After this, four beads on the inner side were made and at the end, nine beads on the outer side of pipe were made. The mesh and sequence are presented in Fig. 2B. For the third sequence, the reinforcement was also taken into account, and the preheating was 150°C.

Heat Input Definition

The defining of heat input is based on the real welding parameters that are presented in Table 1. These parameters are also important when preparing mesh.

From electrode size and welding speed, the volume of deposited material for each bead is determined. The energy input is defined by welding current, voltage, and welding speed.

The heat input definition was made based on the pipe size and welding parameters. The method used in this particular case is the cooled MBD method. The heat is transferred into the weld instantaneously in one or several macro steps. The real weld trajectory is divided into several macro sections. It's deposited in the structure before the computation starts and released following the definition of the macro time steps. The energy/length transferred into the structure is the same as in the real process, but it occurs in another time frame.

The MBD methodology is, to a certain extent, a coarser step-by-step method (Ref. 4). The alternative is transient welding (step-by-step methodology) (Ref. 5).

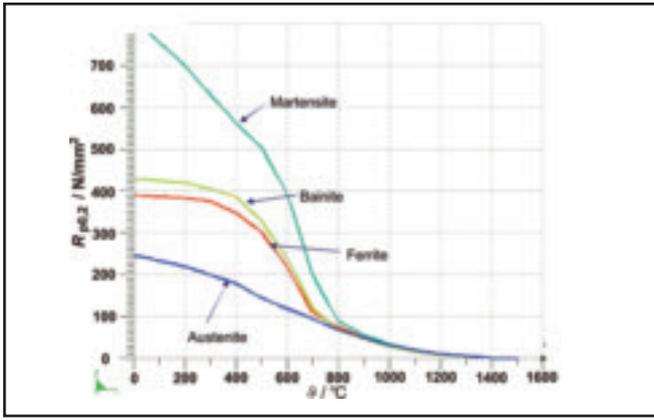
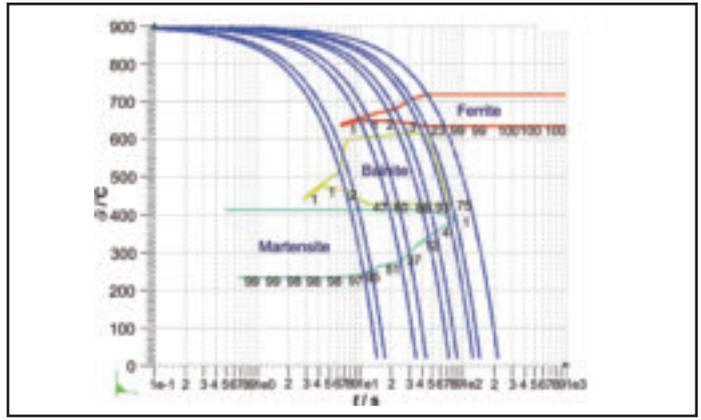


Fig. 5 — Yield stress as a function of temperature and phase.



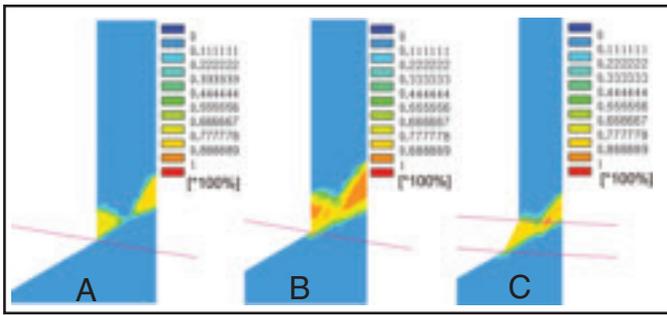


Fig. 9 — Bainite distribution after welding. A — First sequence; B — second sequence; and C — third sequence.

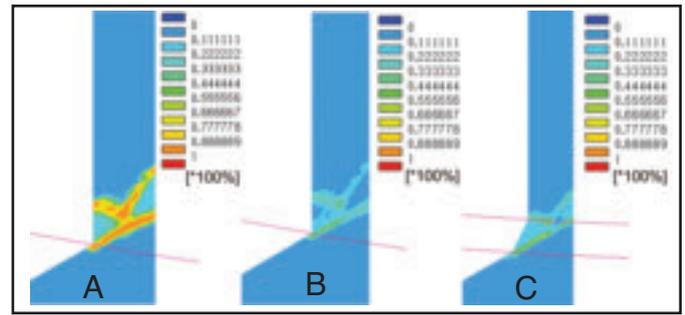


Fig. 10 — Martensite distribution after welding. A — First sequence; B — second sequence; and C — third sequence.

tions on deformation can also be seen in Fig. 7A–C. The deformed shape is multiplied by factor 10, so the deformed shape can be visible. Maximum deformation after welding with the first sequence in the flange area is 7.7 mm. The deformation in the second calculation was 6.3 mm, and after welding with third sequence, the deformation was 3.8 mm.

Beside the deformation, distribution of stresses in the heat-affected zone are calculated. It's shown that there is small compressive stress in the area where the first beads were made — Fig. 8A–C. The highest tensile stress accrues on the surface at the inner side of the pipe and below the surface of last beads welded on the outer side of the pipe.

The results that are presented in Figs. 9 and 10 show the microstructure after welding in the heat-affected cone. Presented in Fig. 9A–C is the bainite distribution in the welding area. The amount of bainite at the welding area in Fig. 9A is 70 vol-%, but in Fig. 9B and C, the amount of bainite is 90 vol-%. On the border between the base material and welded beads is an increased amount of martensite phase, up to 80 vol-% in Fig. 10A where the preheating was not defined, and between 10 and 20 vol-% in Fig. 10B and C where the preheating was 150°C. This is the result of a higher cooling rate on the border with a base material when the preheating was not defined.

Conclusions

For distortion prediction after unique pipe welding, three calculations were made with different welding sequences and clamping conditions. The deformation after the third calculation is acceptable. For further deformation reduction, another calculation with a change in the welding sequence could be made, but the obtained results are suitable for now.

The peak values of stresses are relatively high for this material, but these peaks cover very small areas. Also, these values should be moderated with some simple test welding with similar conditions. The test welding should be simulated as well, so that we can compare if these stresses will cause some cracks or not.

The amount of martensite phase on the border with a base material could be reduced with a higher preheat temperature, but this higher temperature will be hard to reach due to the flange's large heat capacity. Also, the tendency for crack formation is relatively low because the area with a higher portion of martensite is not at the same place as the area with a high value of calculated stress.

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