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Numerical simulation steam generator repairs

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ABSTRACT: The paper describes process of numerical simulation of welding repairs for steam generator. Metallurgical, thermal and thermoplastic calculation were carried out. Process was divided into two separate phases. In the first phase the simple models were used to experimentally verify all input data influencing the calculation. In the second phase, the already verified data were used for actual simulation of all repairs. The results from the second phase were compared with real simulation on real models. The heat source model for 3D simulation is described. Programs SYSWELD were used for welding simulation.

1. INTRODUTION

Producers of key nuclear power station components face an important task how to develop technological defect repair processes required during the power plant lifetime. These processes must be available before the actual plant operation starts and appropriate authorities had granted their approval.

The VITKOVICE j.s.c., a major producer of horizontal steam generators, has extensive experience with repair procedures developing for their components. Based on the experience with steam generator being in service for a long period of time, the areas with frequent defect occurrence were defined and needed repair procedures were developed. Even some of them were carried out in real situations. Working procedures were prepared for different crack sizes and depths without the heat treatment. Designed technology was subjugated to investigation (calculation and experiments), verified, optimized and converted to final suggestion. As a result of a concentrated effort have been developed technological repair procedures during service condition and numerical methods of determination interference of lifetime steam generators.

2. DEVELOPMENT OF TECHNOLOGY WELDING REPAIR

Development of individual technologies wage next way. Technologist of engineer-in-chief division worked up suggestion technological procedures with welding parameters (current, voltage, etc.), method of welding, filler materials and process laying of deposits. On the base requirements of appropriate authorities the technologist defined extent tests, which it is perhaps performed to experimental determination material property in repair area. Producer of steam generator provided a needed materials , so as to mostly approximate real dimension. Specimen were manufactured for testing material properties in repair regions. For numerical simulation needs the experiments were chosen experiments to verify all input data. Needed material properties were provided experimentally or from literature. Technological process was numerically simulated and on the base simulation the process was optimalization. Residual stress determine numerical simulation of repair welding processes were verified with measurement on real pattern. Final technological procedures were designed after execution of all steps. Appropriate authorities had granted the final technological procedures approval.

Institute of Applied Mechanics Brno Ltd. was assigned a task concerning simulation processes of four defined repairs, calculating residual stresses after repairs and consequently to estimate decreased component lifetime. Program SYSWELD [1] by Framasoft+CSI was used for the numerical repair simulation, enabling complete metallurgical, thermal and thermoplastic calculations. Program STATES [2] developed in our Institute was used for determination of influence on component lifetime. The influence is determined following Czech, eastern and western standards.

VITKOVICE j.s.c. have been developed following repair procedures without the heat treatment :

- crack repair in steam generator body
- primary collector sealing grove repair
- blinding of leaking steam generator pipe
- crack repair under anticorrosion layer

3. EXPERIMENTAL PROGRAM

The experimental program as a whole was divided into separate successive phases. In the first phase the small and simple models were used to determine and collect input data for numerical simulation. Thermal cycles were measured by using thermocouples during experiments to set the right thermal loading and thermophysical properties verifications. The models were later cutting up to measure geometry of beads, depth of penetration, AC_1 and AC_3 distance from molten line, position of thermocouples, grain size and hardness. The hardness measurement served to determine metallurgical phase proportion.

In the second phase of experimental program the suggested technologies were tested on the real models and sizes. The experiments were done after numerical simulation evaluation of small models in the first phase solution. The suggested procedures, materials, parameters of welding, welder and technology were the same as in a real situation. Measurement in this phase were used to verify of numerical simulation of real repair.

4. PROCESS NUMERICAL SIMULATION

The numerical simulation process was divided into two separate phases too. In the first phase, the simple numerical models were created for complete verification of all input data representing different parts of a real repair situation. Verification models are shown on Figure 1. Model 1 was used for basic comparison only [5]. The hardness were measured on the indicated axes, if phase proportions corresponding with measurement. A hole drilling method and X-ray diffraction were used to compare residual stresses. Model 2 was used to determine thermal loading deposits in the corner [6]. For real situation we used deposit geometry and their overlay. The model also served to verify thermophysical properties. The experiment was designed to measure hardness after each deposit on the indicated axes and to verify tempering effect. Model 3 was used to determine thermal loading of adjoining deposits [7]. Residual stress were measured using X-ray diffraction. Model 4 is used when different welding parameters are applied to filler part [8].

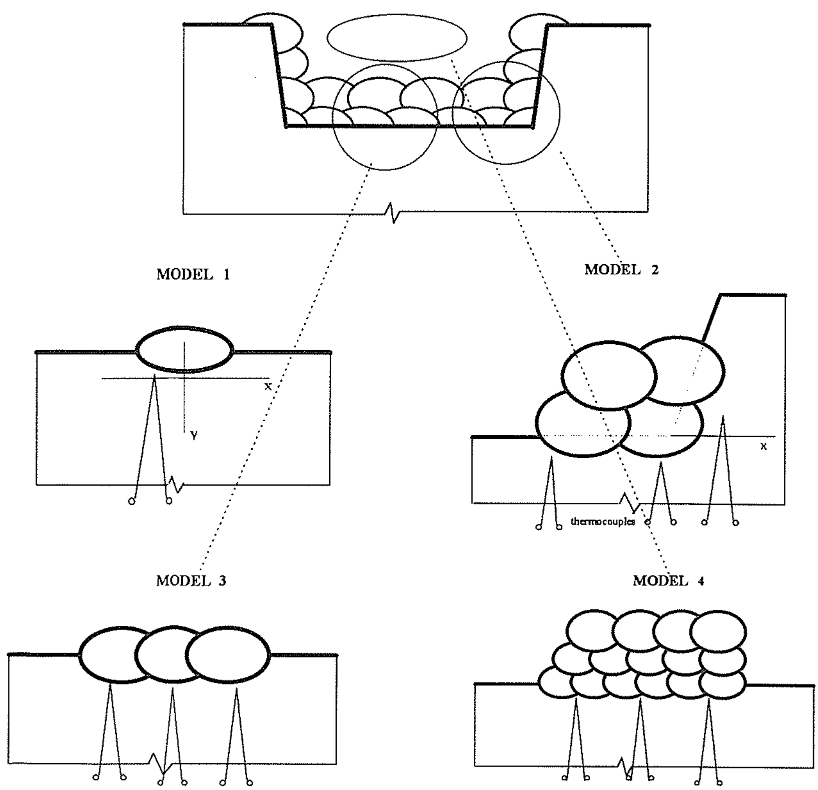

Figure 1. Designed verification models

Verified thermophysical and mechanical properties were used in the second phase of numerical process for real repair simulations. Thermal loading verification had to be done separately for each repair. The results from the second phase were compared with real simulation on real models.

To the after-repair calculated residual stresses the stress caused by anticipated design service conditions were added. The components were finally assessed as to their lifetime. The influence of repairs on the component lifetime was determined by relative cumulative damage which was calculated for designed conditions with and without residual stress.

5. MATERIAL PROPERTIES

The one of the most important input data for numerical welding simulation are correctly identified material properties. Correct results cannot be obtained without the right data. The needed material property values were obtained in VITKOVICE j.s.c. laboratories or from literature based on known chemical composition [3,4]. During the first phase the data from literature were verified using simple models which were further compared with experimental measurements. Chemical compositions of studied basic and filler materials are shown in table 1.

Table 1

Material	C	Mn	Si	P	S	Ni	Cr	Mo
10GN2MFA	0.12	1.07	0.17	0.02	0.017	2.22	0.21	0.57
Sv07Ch25N13	0.09	2.0	1.2	0.03	0.02	14.0	25.0	-
ZIO 8	0.12	2.7	1.0	-	-	12.5	25	-
E-A 898/218	0.1	2.5	0.7	0.025	0.02	10.5	17.5	1.05

A metallurgical calculation requires proper transformation CCT or TTT diagrams. We used the CCT diagram created in our laboratory to carry out numerical simulations. A special Jafe-Holomon's diagram was created for theoretical tempering effect simulation of higher layers on lower layers. Thermophysical properties of α and γ phases presented a separate problem. The data which are temperature dependent were taken from literature (based on chemical composition). These data were verified by comparing thermocouple measurements and calculated temperature fields. Other needed input data for thermoplastic calculations involve dependency of material phase properties and thermal strain on temperature. These properties were measured in VITKOVICE laboratory using fast dilatometry tests, too.

6. INPUT DATA VERIFICATION

Experimental models were also simulated using program SYSWELD and results were compared with measurements on macroscopic sections. Experimental models gave us thermal loading and verified material properties. Comparison measured and calculated temperature in measured point on the central thermocouple on model 2 is shown on the Figure 2. The similar history we obtained on the other thermocouples. Heating and cooling rate was observed. Comparison measured and calculated hardness through heat effected zone (HAZ) on model 2 after first deposit is shown on Figure 3. Verification of tempering effect after the third and fourth deposit on model 2 is shown on Figure 4.

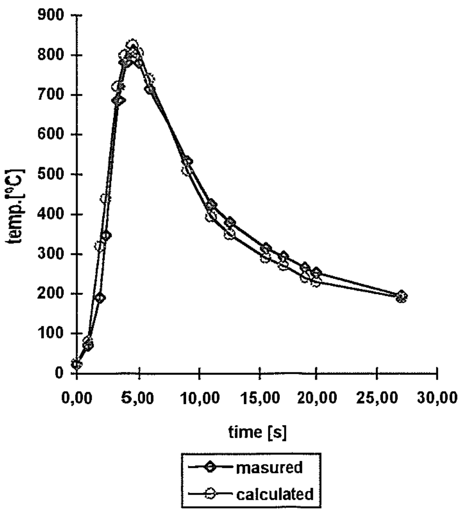

Figure 2. Comparison measured and calculated temperature in measured point

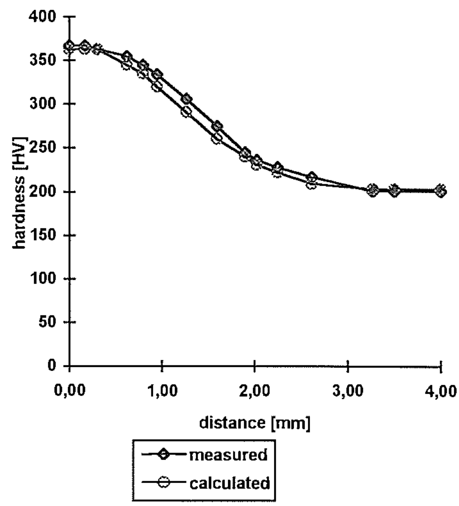

Figure 3. Comparison measured and calculated hardness through HAZ

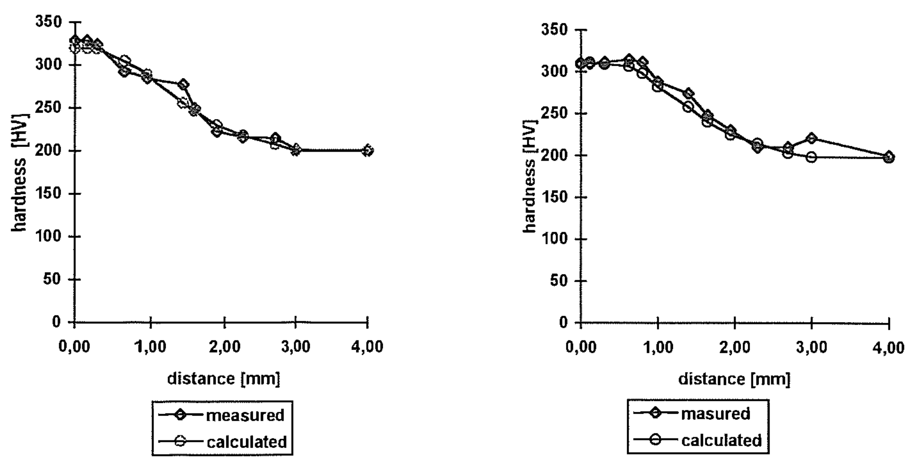

Figure 4. Comparison of hardness through HAZ in the same place after each deposit to verify tempering effect

7. THERMAL LOADING MODEL

Thermal loading selection is a decisive factor for correct welding simulation. It became apparent already during first steps of verification phase that boundary condition of the first kind (i.e. the temperature in nodes) does not yield correct results. The results of phase proportion in HAZ did not correlate with experiments. The differences were also apparent in hardness comparisons.

The right model of thermal loading must take into account relations among heat flux, power input, source location and energy distribution in the arc. In [9,10] such dependency was found and verified. Gaussian surface flux distribution was used for 2D models, but later more precise double ellipsoidal power density distribution was adopted.

$$q_{(x,y,z,t)} = \frac{6 \cdot \sqrt{3} \cdot f \cdot Q}{a \cdot b \cdot c_{1,2} \cdot \pi \cdot \sqrt{\pi}} \cdot e^{-\frac{3 \cdot x^2}{a^2}} \cdot e^{-\frac{3 \cdot y^2}{b^2}} \cdot e^{-\frac{3 \cdot (z - v \cdot (\tau - t))^2}{c_{1,2}^2}} \qquad \{1\}$$

Equation 1 - Double ellipsoidal power density distribution

The heat flux q is depend on the position of heat source x,y,z and time t. The power Q [W], velocity of welding v, times t and τ, and geometry of molten bead a,b,$c_{1,2}$ were measured during all experiments. Parameter f was found during numerical simulation of simple models. Using this model of heat source we obtained results coming very close to actual experiments. The equation {1} was modified on circular movement for blinding of leaking pipe repair.

8. REAL SIMULATION OF REPAIRS

To simulate crack repair in anticorrosion layer area and crack repair in steam generator body were created planar models. Models represent quasi-stationary state where each electrode gradually comes through a calculated middle section the repair zone. Thermoplastic calculation was carried out under plain strain condition.

To simulate blinding of leaking steam generator pipe we created 3D model taking into account behavior of surrounding pipes (Figure 5,6). The heat source trajectory was a circle. Based on source angular velocity we calculated its position and the heat flux was assigned to points located in the area of welding. The molten area size was determined by experiments. Both time delay before full output is reached and decrease to zero output after 410° degrees trajectory was taken into account. Thermal loading was verified using thermocouples on real models (Figure 7). The sketch of this repair is shown on Figure 8. HAZ has been monitored too.

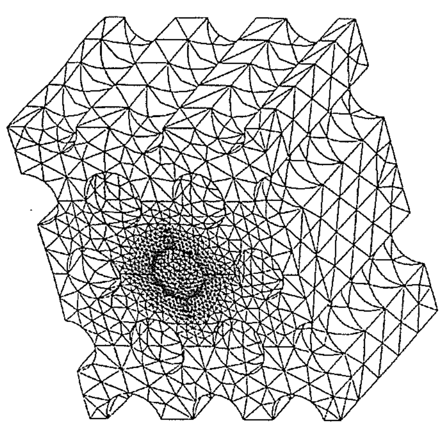

Figure 6. Numerical model of leaking pipe repair

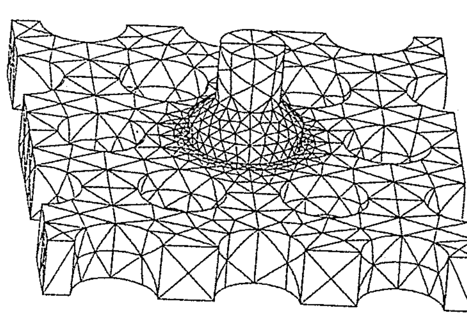

Figure 7. Plug and anticorrosion layer

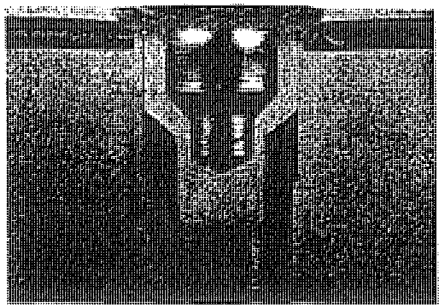

Figure 6. Experimental model of blinding

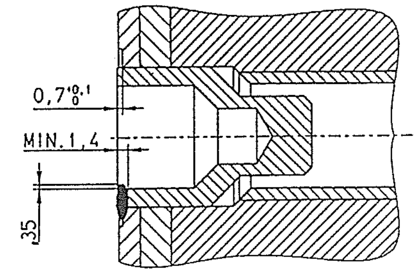

Figure 8. Sketch of repair

The sealing grove repair model was also designed in 3D with 3 or 6 deposits (Figure 9). It is depend on the used technology of repair. The model was created to include bolt connection behavior together with its ligaments during the repair. Grounded surface deposits were not taken into account. Close attention was paid to the base material in the opening neighborhood. Heat source movement was calculated as translation - equation {1}. Thermal loading was verified using thermocouples. The numerical model after restoration of grove is shown on Figure 10.

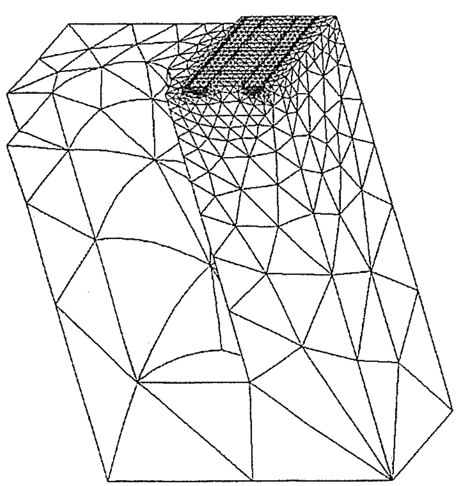

Figure 9. Numerical model after repair

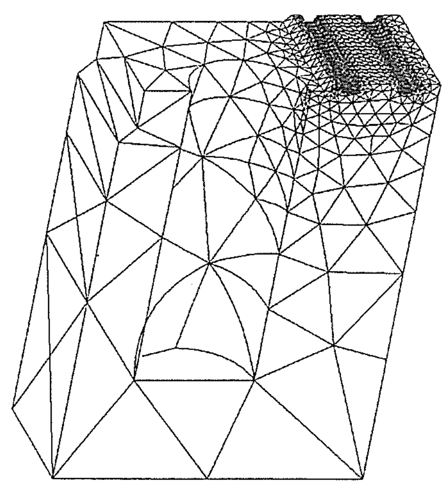

Figure 10. Model after restoration of grove

9. FATIGUE ASSESSMENT OF WELDED STRUCTURE

Residual tensile stresses have negative influence on the structure lifetime and its brittle fracture resistance. Residual stresses create balanced system of inner forces, which exists even under no external loading. Its existence may negatively influence especially a steel with transitory behavior. When subjected to temperatures bellow null ductility temperature toughness, the construction exhibits brittle limit state without any external loading.

Under repeated loading the residual tensile stresses may cause a growth of defects above acceptable limits even during the first cycle of external loading. It is known that stresses caused by external loading are added to residual stresses which results in their overall increase. Under overloading, the stresses are redistributed to the areas of lower level. However the existence of residual stresses themselves will influence hysteresis loop, which finally defines dependency of total σ_t stress range on total ε_t strain range. Residual stresses thus effect amplitude of cycle stress asymmetry and deformation, which in turn influence the number of acceptable cycles [No]. Experience gained by experimentally influencing the hysteresis loop by residual stresses is especially important in nuclear power plant components working under cyclic conditions.

10. CONCLUSION

The VITKOVICE a.s. has developed four separate technologies for various type repair without heat treatment. These technologies are based on great number of experimental tests and measurements together with actual repair simulation on life-size patterns made of real materials. Preceding numerical simulations had a major impact on final procedure and represent a key factor in repair simulation analysis. The VITKOVICE a.s. can offer these technologies to a customer now.

We can say the welding simulation is possible under certain circumstances. To obtain the results close to a real situation a great number of verification experiments had to be carried out. Of course the costs of experiments has to be considered. The final results are known input mechanical material properties under high temperature and temperature loading for given designed parameters. It is advantageous that even when technological design is altered, the only parameter needed to be verified is the thermal loading and whole simulation process can be easily carried out. The experiments can be used to determine the thermal loading based on a known power input without strenuous verifications process.

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