APPROACHES FOR NUMERICAL SIMULATION OF HIGH FREQUENCY TUBE WELDING PROCESS

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ABSTRACT. Welding processes and installations used nowadays are mainly developed on practical experience and analytical calculations because suitable numerical simulation approaches are developed not enough. Nevertheless, high frequency induction tube welding is a very complex three-dimensional dynamic process, where the electromagnetic and thermal characteristics are distributed not only in space but in time as well. Therefore a more profound detailed investigation of the induction tube welding process can be only done by numerical modelling. Full and local three-dimensional transient numerical models of induction tube welding process with continuous movement of the welded tube have been developed and tested. Coupled electromagnetic and thermal analyses are carried out at each time step of simulation for correction of temperature dependent electro- and thermo-physical material properties. Thermal analysis includes simulation of thermal losses by convection and radiation taking into account view angles. Voltage or current of the induction coil can be individually input into electromagnetic analysis at each time step. This approach allows simulating “quasi” steady-state as well as transient operation modes of the welding process. The simulation models have been realized using Finite Element Method e.g. on the basis of commercial program package ANSYS.

INTRODUCTION

For the production of tubes made of steel (ferritic or austenitic) or steel coated with zinc or aluminium as well as made of aluminium, brass, copper or zinc various conduction or induction welding technologies are used in industry. The longitudinal seam welding of the tube can be done by the use of high-frequency (HF) resistance heating (conductive heating) or inductive heating.

The HF induction welding process is executed with the application of a high frequency parallel or series resonant circuit converter for the energy supply. The welding is effected by a ring shaped or profiled inductor, which includes the tube and induces a high frequency current into it. The current passing the strip edges heats the material with an increasing temperature towards the welding spot. The welding itself is now here effected without any additional material by pure pressure from upsetting rolls. The welding beads are trimmed in hot condition behind the upsetting rolls on the outside and on the inside if necessary.

Contrary to other methods of induction heating where the heating is affected directly next to the inductor, the heated area is mainly outside the inductor loop area at longitudinal seam welding. The currents induced under the inductor are passing the back of the tube, then the edges of the strip and meet at the welding spot. There then the required welding temperature of about e.g. 1400°C is achieved.

HIGH FREQUENCY APPLICATIONS FOR THE TUBE PRODUCTION

For the production of tubes made of steel or other metals, conduction or induction welding and various induction heating technologies used in industry today are shown in Figure 1.

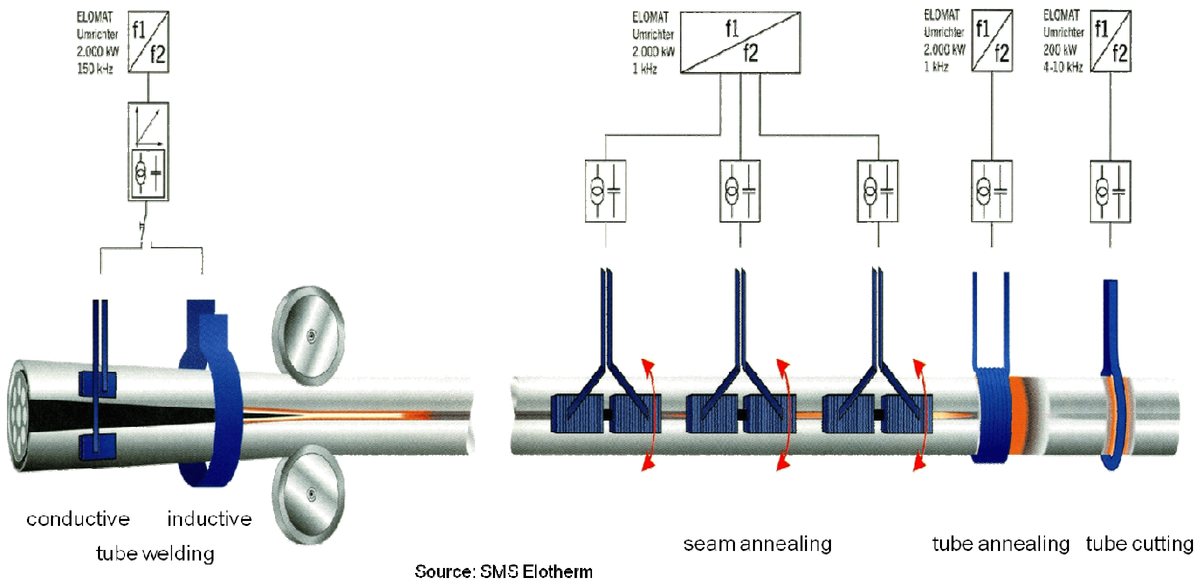

Figure. 1. HF applications and induction applications for the production of tubes (Courtesy: SMS ELOTHERM)

The longitudinal seam welding of the tube can be done by the use of high-frequency (HF) resistance heating (conductive heating) or inductive heating as explained more in detail in following chapter. Due to high cooling rates during the welding process, a different metallurgical structure and different mechanical properties compared to the base material occurs in the seam and in the heat affected zone. An induction seam annealing installation can be integrated in the welding line to achieve a homogeneous grain structure on the whole circumference. If the annealing of the complete tube is necessary from metallurgical point of view an induction tube heating system can be used. A cutting installation is arranged at the end of the tube production line in order to cut the tubes into conventional lengths. This unit can be operated mechanically, e.g. as a travelling saw, or in certain cases even by induction. In this latter case, the tube is heated by a short one turn inductor and then separated by a tension pulse in axial direction.

The high frequency tube welding involves the application of a high-frequency alternating current in the range 100 - 500 kHz, with the tube forming and energy input operations being performed by separate units. This welding method simultaneously utilizes pressure and heat in order to join the strip edges of the open-seam tube together without the addition of a filler metal. Squeeze and pressure rolls in double- or multi-roll weld stands bring the edges of the open-seam tube gradually together and apply the pressure necessary for welding (see Figures 2 and 3). High-frequency alternating current offers a number of benefits as energy source for generating the heat required for the welding process. Due to the skin and proximity effect the current thus flows along the strip edges of the open-seam tube to the point at which the strip edges abut (welding point), and the ensuing concentration. Below the Curie point (768 °C), the depth of current penetration only amounts to a few hundredths of a millimetre. Once the steel is heated above this temperature, it becomes non-magnetic and the current penetration depth rises to several tenths of a millimetre at frequencies in the region of 450 kHz.

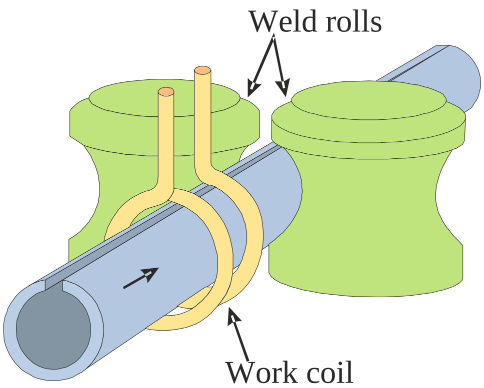

Figure. 2. Schematic of the longitudinal high frequency seam welding of tubes using inductive welding

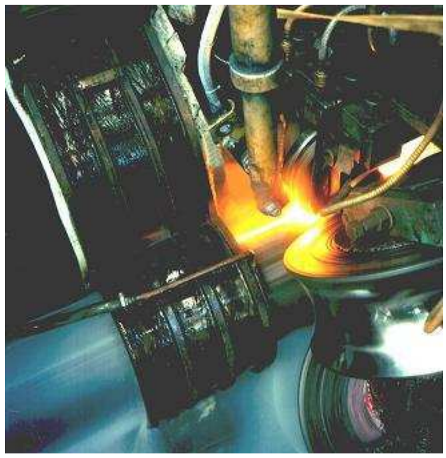

Figure. 3. Example of the high frequency induction welding of tubes

The welding current can be introduced into the open-seam tube both by conductive means using sliding contacts and by inductive means using single or multi-wind coils. Consequently, a distinction is made in the nomenclature between high-frequency induction (HFI) welding and high-frequency conduction welding.

Welding processes and installations used nowadays are mainly developed on practical experience and analytical calculations because suitable numerical simulation approaches are developed not enough.

High frequency induction tube welding is a very complex multi-physical three-dimensional process. Additionally, the induced current and temperature are distributed not only in space but in time as well. The electromagnetic-thermal process parameters are depending on the geometry of the inductor, impeder and in particular on the tube (e.g. wall thickness, incoming angle etc.), the operation parameter, like total power, inductor current, frequency, welding feed etc. and finally also on the material data like electrical conductivity and other, which are temperature dependent or in case of magnetic permeability temperature and magnetic field strength dependent.

All of these influence factors and physical correlations have to be taken into account for the design and optimization of the HF induction tube welding process. Therefore a more profound detailed investigation of the physical relations of the process can be only done by numerical modelling. In order to simulate the three-dimensional (3D) “quasi” steady state and if necessary transient mode of an induction tube welding system, special numerical models are required. The models must simulate the heating process distributed in space and in time. That is why the models of induction tube welding must be based on special algorithm providing a time loop additionally to coupling between electromagnetic and thermal analysis.

NUMERICAL MODELS OF INDUCTION TUBE WELDING PROCESS

The developed numerical models of induction tube welding process with continuous movement of the tube are based on one specially created algorithm shown in Figure 4.

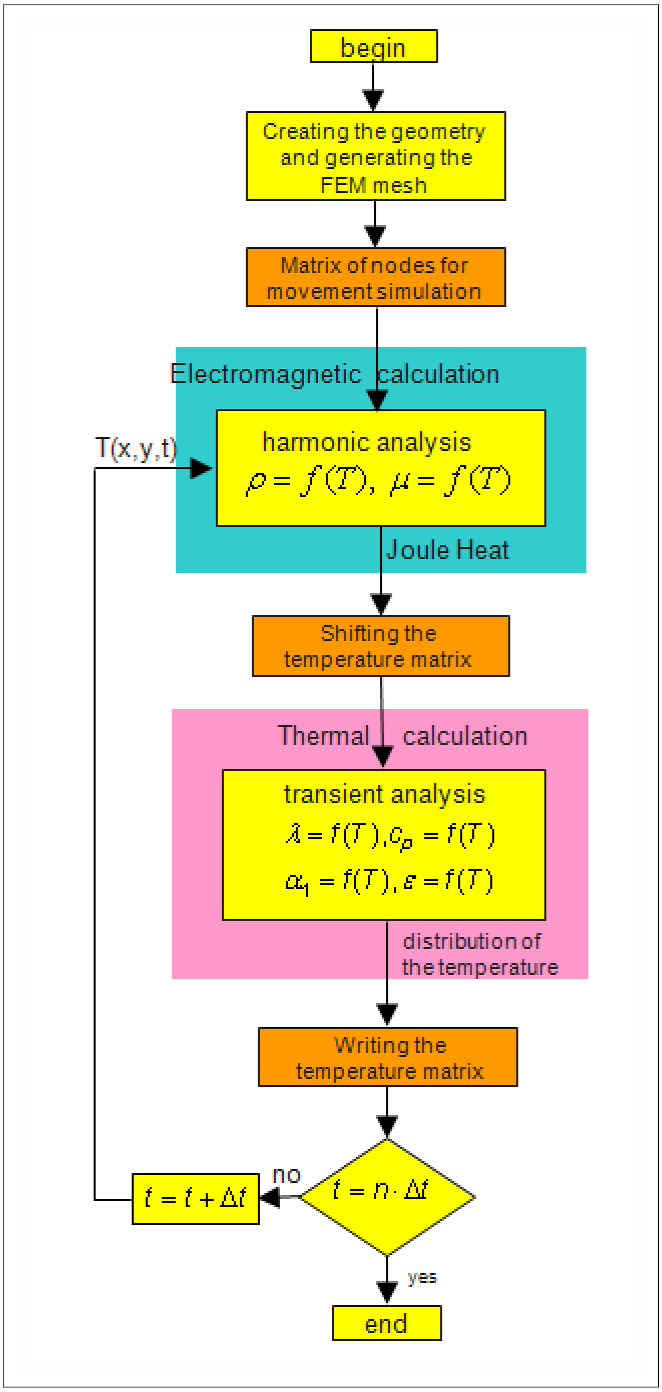

Figure. 4. Algorithm of transient coupled electromagnetic-thermal analysis with the tube movement

For numerical simulation the continuously running physical heating process is replaced by big enough number of time steps. Electromagnetic and thermal analyses are carried out at each time step of simulation. The Joule heat distribution in the tube, calculated in the electromagnetic analysis, is used as an excitation for the thermal one at the running time step. Temperature dependent electro-physical material properties are corrected for electromagnetic analysis at the running time step according to temperature distribution in the tube after the previous time step. Thermal analysis includes simulation of thermal losses by convection and radiation from all open surfaces of the calculated system. Heat flux by radiation is calculated taking into account view angles. Temperature dependent properties of steel used for simulation are shown in Figure 4.

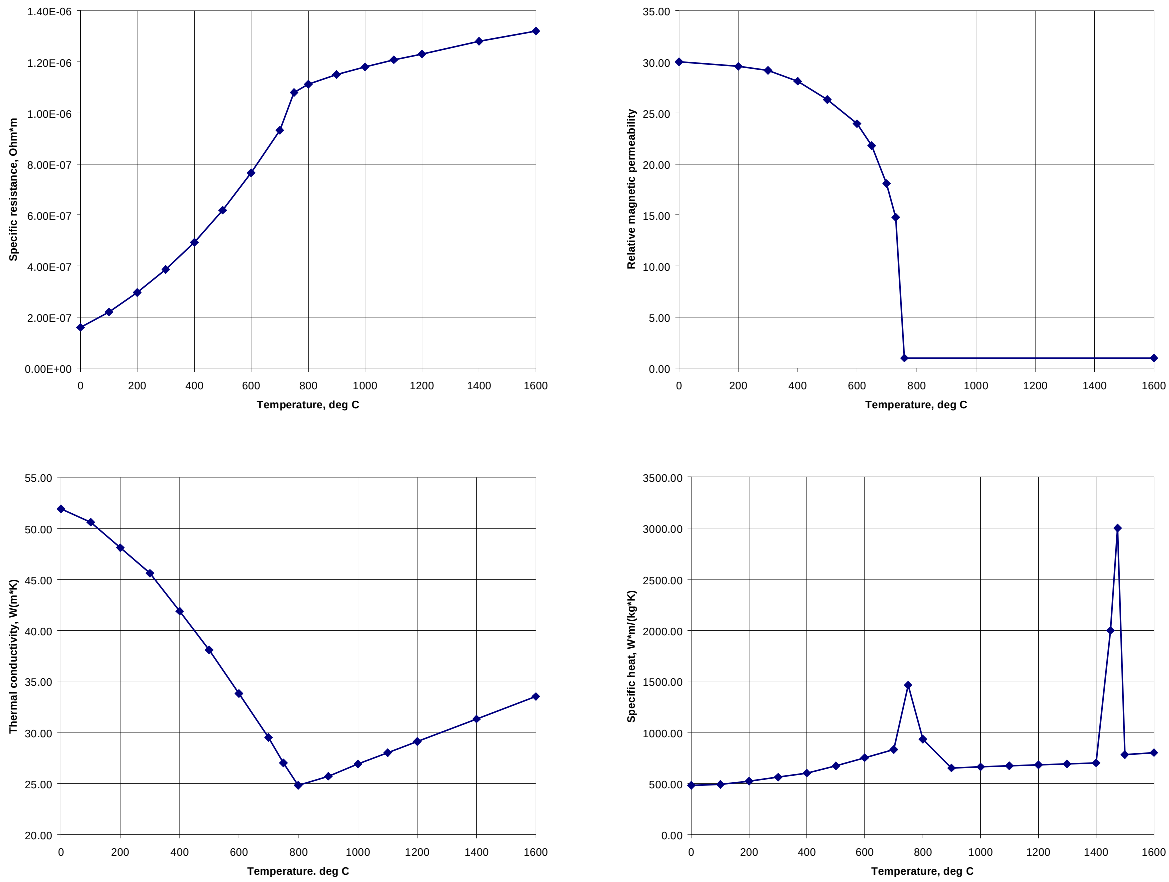

Figure. 4. Electro-physical and thermo-physical properties of steel used in the models

Input of voltage or current of the induction coil is individually input in electromagnetic analysis at each time step. This approach allows simulating various kinds of transient modes. The “quasi” steady-state operation mode can be reached as well via transient one after long enough time.

One robust way to implement movement of the workpiece is based on shifting the temperature field before each time step of thermal analysis [1]. It is very effective for simulation of induction heating systems with continuously moved endless workpiece of constant cross-section. However, uniform numerical mesh in the workpiece in the direction of motion is required for this approach. Speed of the workpiece is taken into account via values of simulation time steps. This approach was modified for the tube welding process to run with non-uniform mesh in the tube which is very important for tube welding simulation. Arbitrary simulation time steps can be applied in this case as well.

Two 3D transient numerical models of the induction tube welding process with continuous movement of the tube have been developed according to the created algorithm. The models are realized using Finite Element Method on the basis of commercial program package ANSYS.

Full model of the welding system includes the welded tube with V-angle, the induction coil, impeder (see Figure 5) and the surrounded air which is necessary for spreading of magnetic field. FEM element mesh in the tube has to be very fine because of small electromagnetic penetration depth at high frequency. Only a proper chosen non-homogeneous mesh allows reaching an acceptable compromise between the total amount of elements and the computer runtime needed for simulation.

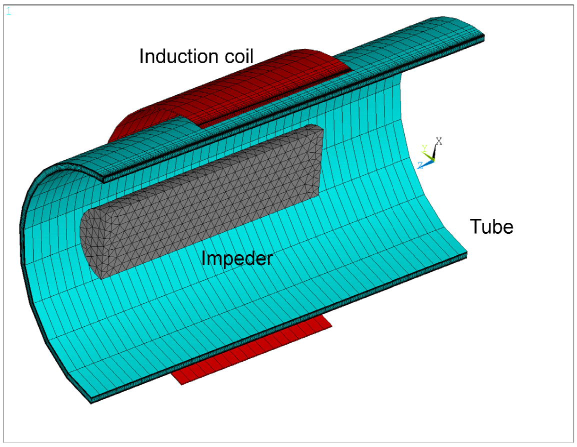

Figure. 5. Geometry and FEM mesh in the tube in the full model

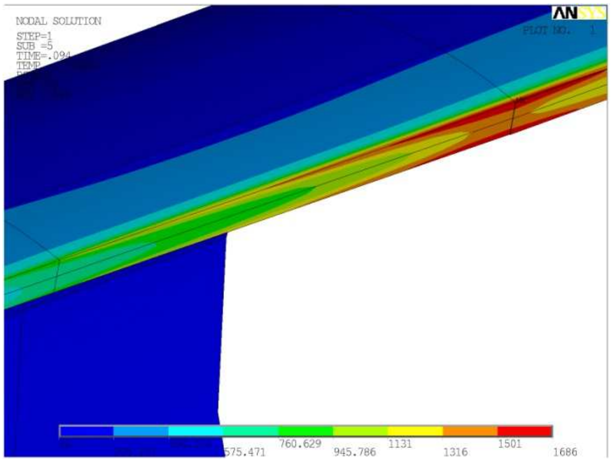

Figure. 6. “Quasi” steady state temperature field in the tube received by the full model

In the presented approach the tube edges are of fixed shape even above the melting temperature. That is why the numerical prediction of temperature can exceed the melting point. One example of temperature distribution in the welded tube edge is shown in Figure 6. Temperature distribution in the second welded edge is symmetric to the shown one. Before the welding point temperature grows because of eddy currents induced in the pipe. After the welding point no currents are running, so temperature drops down as a result of thermal equalization.

The full model is absolutely necessary for parametrical study and optimization of the induction system geometry and electrical parameters of the induction coil and the other process improvements.

The second model, which is called local, includes the welded tube and the air surrounding only (see Figure 7). In spite of the full model, the current is implemented directly into the welded edges of the tube like it is made in HF conduction welding process.

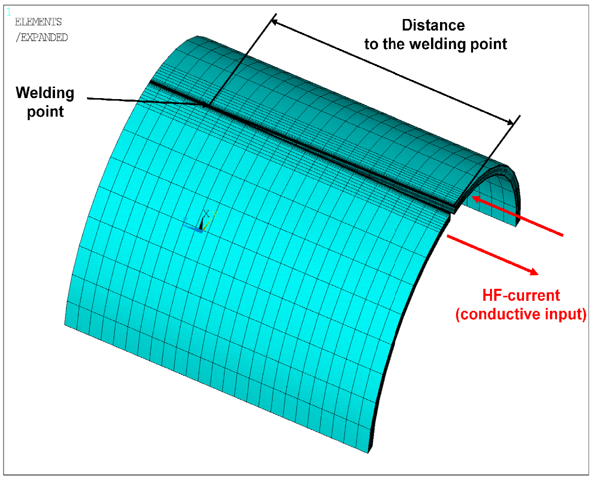

Figure. 7. Geometry and FEM mesh in the tube in the local model

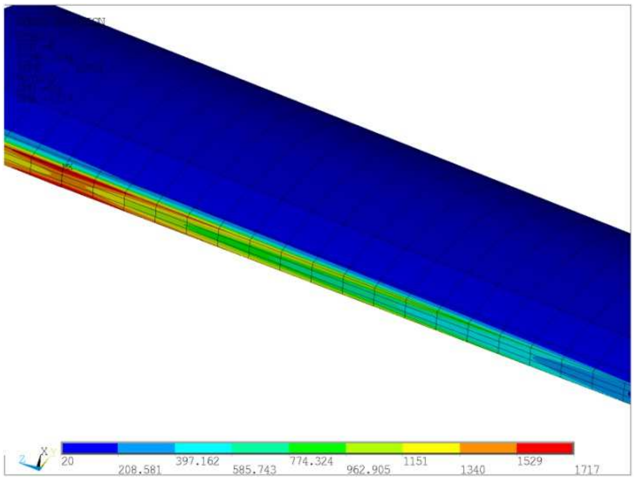

Figure. 8. “Quasi” steady state temperature field in the tube received by the local model

The local model approach allows increasing the element amount in the tube without rising of the runtime. It is necessary for deeper analysis of electromagnetic and thermal effects directly in the region of welding point. One example of temperature distribution in the welded tube edge received by the local model is shown in Figure 8. Temperature distribution is very similar to the results from the full model if the distance from the current implementation to the welding point is chosen in a proper way. In front of the welding point temperature grows because of eddy currents induced in the pipe. Like in the previous case, no currents are running after the welding point, so temperature drops down as a result of thermal equalization

The local model is very effective for investigation of electromagnetic, thermal and other effects around the welding point.

To compare the both developed full and local models, temperature profiles over the tube wall thickness in the welding point are shown in Figure 9.

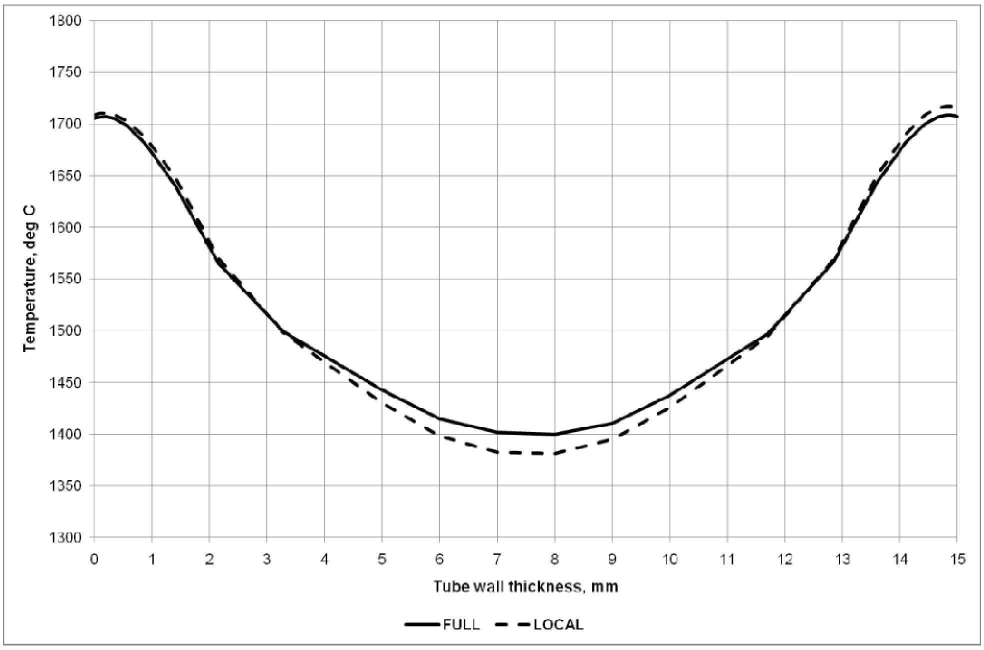

Figure. 9. Temperature profiles over the tube wall thickness in the welding point received by full and local models

The temperature level at the welding point depends on power which is defined by the given induction coil current or voltage. This current or voltage should be tuned to reach the reference temperature given for the certain point of the tube.

Difference between the temperature curves does not exceed 20 K in the middle part of the tube edge. Because of the welded edges in the V-angle are not parallel to each other, the temperature profile is of small asymmetry.

CONCLUSIONS

High frequency tube welding is a very complex process with various physical phenomena. Detailed investigation and optimization of the induction tube welding process can be only done by numerical modelling. Full and local three-dimensional transient numerical models of induction tube welding process with continuous movement of the welded tube have been developed. They are based on coupled electromagnetic and thermal analyses with temperature dependent electro- and thermo-physical material properties. The full model is absolutely necessary for parametrical study and optimization of the induction system geometry and electrical parameters of the induction coil. The local model is very effective for investigation of electromagnetic, thermal and other effects around the welding point. Temperature profiles over the tube wall thickness in the welding point received by full and local models are very similar if the distance from the current implementation to the welding point is chosen in a proper way.

REFERENCES

[1] Galunin, S.; Zlobina, M.; Blinov, K.; Nikanorov, A.; Zedler, T,; Nacke, B.: Numerical analysis of coupled physics for induction heating of movable workpieces. Proceedings of International Scientific Colloquium Modelling for Electromagnetic Processing (MEP2008), Hannover, Germany, October 27 – 29, 2008, pp.59-64