Computation and analysis of temperature distribution in the cross-section of the weld Vee

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ABSTRACT

Temperature distributions in the cross-section of the weld point are calculated through two-dimensional coupled electromagnetic and thermal FEM analyses. A specific development, using FLUX2D, has been done in order to take into account the tube walls' movement towards each other as they approach the weld point.

Due to hourglass shape of the heated zone in medium– and thick-wall tube, cold weld condition near midpoint of tube wall limits welding speed. A parameter study of the influence of welding frequency is carried out at 100, 200 and 300 kHz. The temperature in the center of the wall is kept as a reference by adjusting the current in the Vee. Results include temperature development in the center and on the surface vs. time, isothermal lines and temperature in cross-section at weld point.

INTRODUCTION

The longitudinal induction welding process has been widely used in the tube & pipe industry for many decades. However, even today, the process, with its complex relationships between key parameters, is not fully defined.

In recent years the welding process has also become much more complicated. Global competition has pushed the need to weld a much wider variety of materials in ever increasing d/t ratios which were thought to be impossible just a few years ago. This technological need and a desire for greater throughput at higher quality indicate that much is being demanded of a process that is still not totally understood.

An example of a typical welding problem is a cold (paste) weld condition near the cross sectional center of a medium- or thick-wall pipe, which limits weld speed. The mill can have additional capacity and the welder additional power, but if certain criteria are not met, the cold center may surprisingly and unfortunately limit maximum speed. If the temperature differential in the weld zone is excessive and we attempt to compensate with additional power, the edges of the strip can be significantly overheated causing molten material to drop onto the impeder. One or both of these conditions can also deteriorate weld quality.

A more demanding process, together with the introduction of solid-state welders, has led to an increasing effort to understand the high-frequency tube and pipe welding process. This effort includes identification of the parameters in the process and how they affect weld quality. It has resulted in a number of technical papers and fundamental works being published in recent years. Several papers [1, 2] discuss the influence different parameters have on the temperature distribution in the weld Vee, in both x and z directions (see figure 1), and the resultant heat affected zone (HAZ).

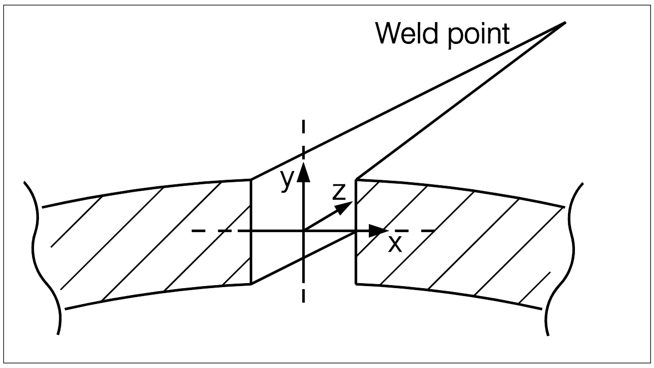


Figure 1 Weld Vee geometry with co-ordinate axes

This paper discusses our examination of the temperature distribution at different stages in the weld zone, that is, the development of temperature distribution in the x-y plane on its way towards the weld point. See figure 2. The simulations are carried out with the commercially available software FLUX2D from CEDRAT.

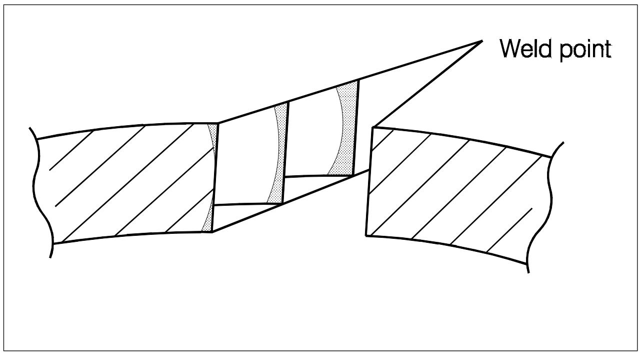


Figure 2 Development of temperature distribution towards weld point

For what purpose can we use the results of these simulations? We can study the influences of different parameters on the temperature distribution across the weld, such as frequency, weld speed, Vee angle, coil-to-weld point distance, non-parallelism in the Vee, etc. And we can use the results for further calculations. If we know the temperature history of the material, we can predict the μ-structure of the HAZ. With known temperature profile in the weld point, we are able to study the material flow and squeeze-out of the oxides during the action of the weld rolls.

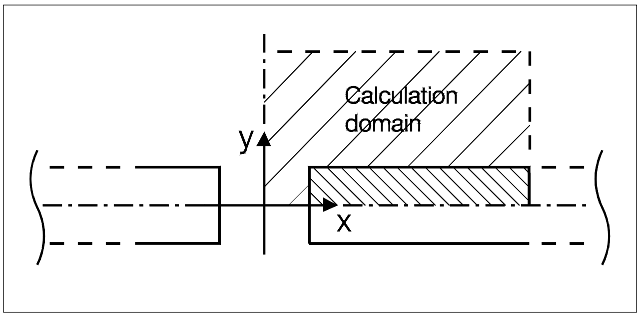
DESCRIPTION OF THE MODEL AND MODELING TECHNIQUE

The fact that the electromagnetic field distribution for tube welding setup is highly three-dimensional complicates an analytical simplification of the problem. One way of understanding the problem better is through numerical calculations. A calculation on the entire problem in three dimensions with coupling between the electromagnetic and thermal parts, using complex non-linear material properties, is not possible with the software commercially available today.

The objective therefore is to represent part of the problem in a two-dimensional model. When doing so, we have to keep in mind the simplifications introduced and their effect on the final result. The model must represent the actual system, but be simple enough to make the computations run sufficiently fast. Numerical calculations are very hardware demanding and time consuming, especially when there is coupling between the electromagnetic and thermal parts of the problem.

In this paper, we look at a cross-section of the weld Vee perpendicular to the tube axis. In the confined space of the weld Vee, the use of a 2D model can be justified. The Vee current's main component is in direction of the weld point (Z). Since the flux lines are perpendicular to the current, they will be in the X – Y plane (Fig.1). The outer diameter of the tube is assumed to be big enough for us to disregard its curvature for the small part of the problem that we have extracted. Because of the current's concentration in the Vee and the speed of the process, it is valid to omit parts of the tube beyond a few thermal penetration depths from the model. The Vee walls are assumed to be parallel during the calculation. In addition, the impeder's influence on the field distribution locally in the Vee is disregarded due to its distance from the inner tube wall. Based on these assumptions, the current distribution is symmetric on both sides of the tube wall centerline. Hence the calculation domain can be reduced to one quarter of the Vee cross-section; see figure 3.

Figure 3 Cross-section of the Vee.



During tube welding, the Vee walls gradually move closer to each other as they approach the weld point. An important physical effect of the actual process, the proximity effect which increases as the strip edges get closer to the welding point, will be ignored if this movement is not included in the computation. In our calculations, the distance between the tube wall and the symmetry axis is reduced between each time-step. How much the reduction is depends on the current time-step, Vee angle, mill speed and distance between coil and weld point.

Considerations regarding the mesh has led us to stop the movement when the distance between the tube wall and the symmetry axis is at a minimum distance of 1/25 of the wall thickness; see figure 4.

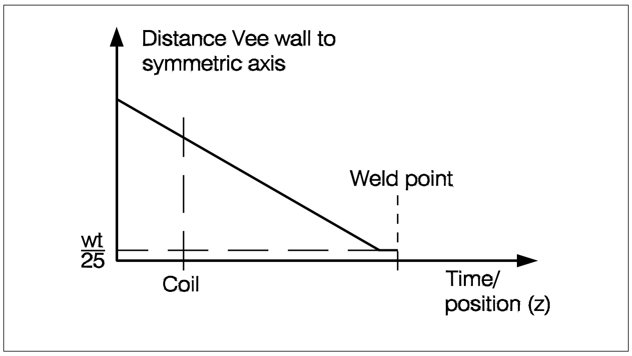


Figure 4 Distance between Vee wall and symmetry axis vs. time

THE FLUX 2D CALCULATION SEQUENCE [3]

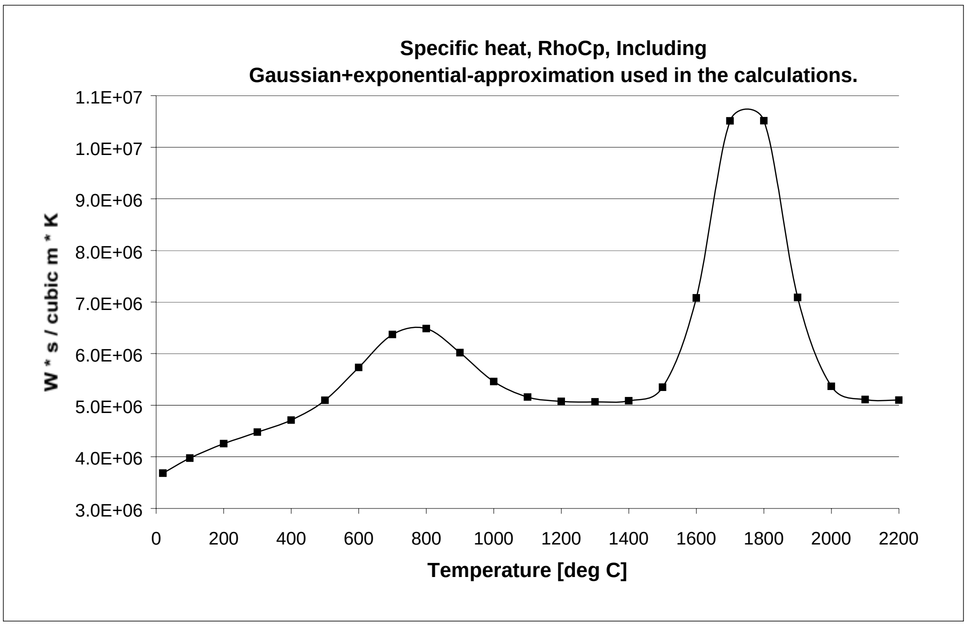
Due to the strong temperature dependency in the material properties, good results for the weld Vee are only attainable if there is coupling between the electromagnetic and thermal parts of the problem. FLUX2D deals with this by first solving the steady state magnetic part of the problem with computed material properties for a given initial temperature. This temperature can be constant over the entire region or it can be distributed according to another calculation of the same geometry. In our case, it is a uniform temperature of 20°C for the entire calculation domain. The Vee wall current is set by connecting the FEM problem to an external circuit [4]. The steady state magnetic computation gives the eddy current and, finally, the dissipated power distribution, which is used as source for a transient-thermal computation. New temperatures are computed for every node of the geometry depending on the power sources and the time of heating, i.e, the time step. From the curves and functions defining the material properties, new properties for each node are found. Based on these new properties, a new steady state magnetic computation results in a new solution for the magnetic vector potential and, hence, a new distribution of the eddy currents and power. This gives ground for a new transient thermal computation and, therefore, a new temperature distribution. This procedure is repeated until the specified accuracy is reached and the program can move on to the next time step.

MATERIAL PROPERTIES

Our calculations are based on the most commonly used material in pipe production, low-carbon steel. The complex nature of this material presents a considerable problem for numerical calculations because it involves non-linearities due to saturation and drastic change of the magnetic properties at the Curie temperature. Regions with temperatures above 760°C therefore have a much higher electrical penetration depth, giving a wider cross-section for the current. The result is reduced power densities locally and a slower temperature rise.

Rapid changes in material properties, combined with a steep temperature gradient over a very limited area of the geometry, complicate matters considerably. Great care therefore must be taken, with respect to mesh and time-steps, to avoid non-converging calculations. In addition, material properties as a function of temperature, and especially specific heat, have to be smoothened somewhat. Required energy for the phase transformation at Curie temperature is represented with a Gaussian distribution in the property of the specific heat. For numerical reasons we have used the same kind of distribution to incorporate the large energy needed to melt the steel; see figure 5. As this curve shows, melting takes place during the temperature interval between 1550°C and 1725°C. The distinct temperature plateau caused by melting will be less clear in our temperature curves. It will, however, be easier to determine how far the melting process has proceeded.

Figure 5 Specific heat for steel used in simulations



RESULTS OF THE SIMULATIONS

A minimum temperature is required in the cross-sectional center of the tube to avoid cold weld condition. This temperature is a function of the applied weld roll pressure. To compare the different temperature distributions, we must have a reference point. In this case a temperature of 1250º C in the center point (x=y=0).

In the simulations presented in this paper, all parameters, except current and frequency, are kept constant. The current must be changed according to the chosen frequency in order to get the requested reference temperature. Temperature distributions are examined on the basis of three different frequencies: 100, 200 and 300 kHz. Parameters kept constant throughout these simulations are:

- Calculation time is 1.2 seconds, which, with the chosen Vee length, gives a weld speed of 14.6 m/min (48 f/min).
- Vee angle is 3º.
- Wall thickness is 12.7 mm (0.5").

In figure 6, the temperature lines for the center of the tube wall indicate that the temperature rise increases for higher frequencies as the strip edges approach the weld point. This confirms that the proximity effect is stronger at increased frequency.

Due to considerations regarding the mesh in our model, the movement of the edges stops when the gap between wall and centerline equals wt/25. In the model, the impact of the stronger proximity effect, therefore, is reduced for the last 6% of the weld zone.

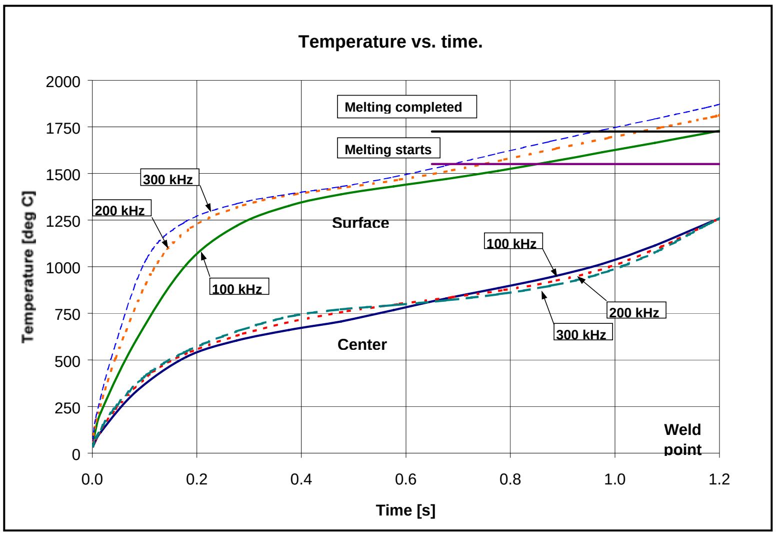


Figure 6 Temperature development in the center and on the surface vs. time

Figure 7 a, b and c, show the isothermal lines in a cross-section of the tube wall at the weld point for 100, 200 and 300 kHz, respectively. They show a distinct difference in the amount of molten material.

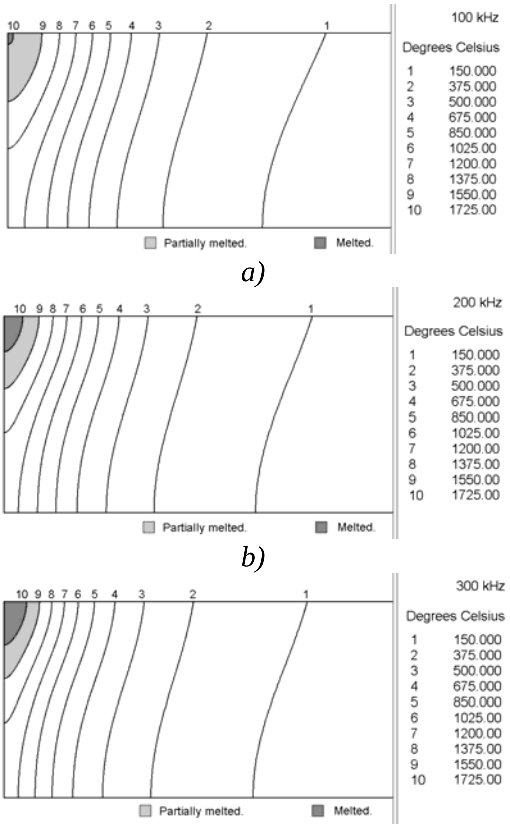


Figure 7 Isothermal lines at weld point (a) 100 kHz, (b) 200 kHz, (c) 300 kHz.

Figure 8 graphs the Vee temperature distribution along the weld line. The temperature in the region close to the Vee wall corners reaches the melting point for all three frequencies. It is evident that the maximum temperature of the corner, as well as the size of the zone that melts, increases with frequency. In reality, steel has a narrower melting interval than shown in our Gaussian representation of the melting energy by the RhoCp-value (Figure 5). On the right side in Figure 8, we have indicated how a narrower melting interval gives a plateau in the temperature distribution. The temperature will not rise above the melting temperature of 1550º C until melting is completed. Molten material can drop from the Vee wall or be thrown away by the current forces. This alters the geometry of the Vee and consequently influences the power distribution. It is our intention to describe the frequency's influence on the temperature distribution, and not what occurs during melting.

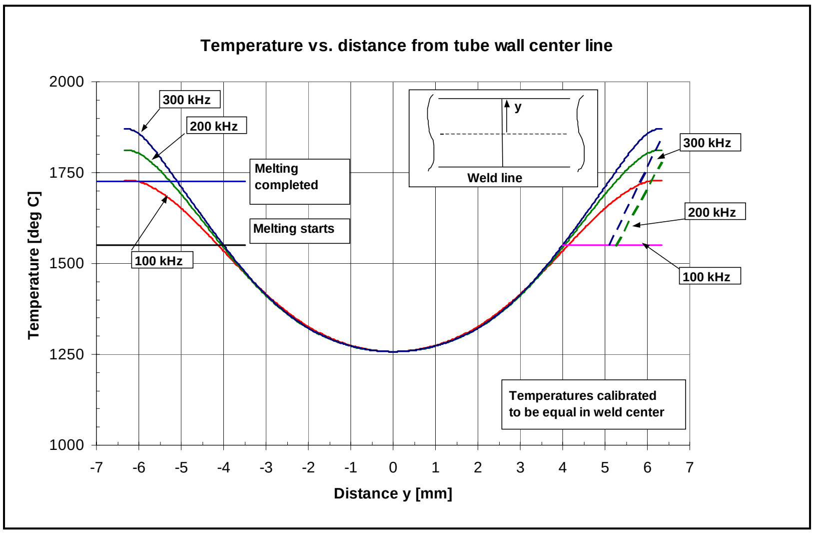
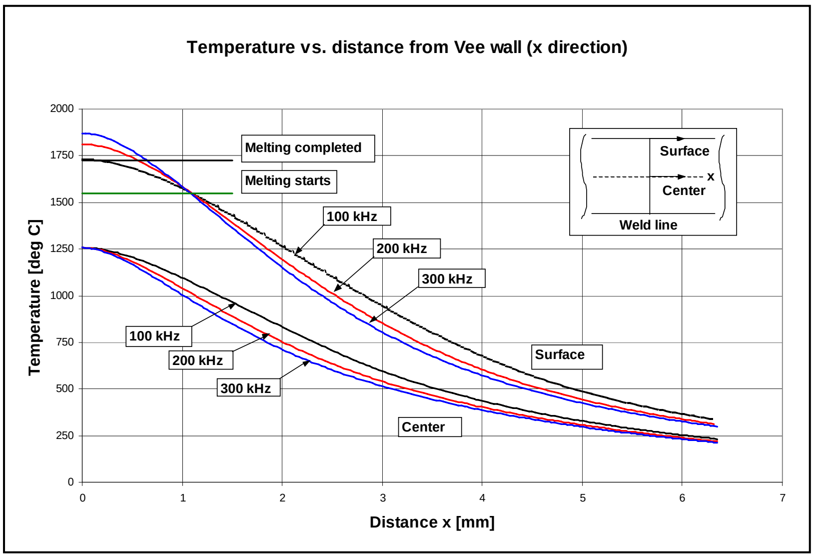


Figure 8 Temperature in cross-section



at weld point (y-axis)
Figure 9 Temperature distribution at weld point (x-direction)

Figure 9 shows a reasonable similarity in the different temperature distributions, especially regarding the center of the wall. Looking closer at the diagram, we see that the temperature decreases faster in x-direction from the weld line at higher frequencies. An adequate measure is the width of the zone (one half) in the center of the tube wall with a temperature within 90 - 100% of the center temperature. The measured widths are 0.65 mm, 0.73 mm and 0.89 mm at, respectively, 300, 200 and 100 kHz.

The relative values of energy input to the weld zone for 300 and 200 kHz are 90 and 93%, respectively, of the value for 100 kHz. The temperature charts indicate a wider heated zone for 100 kHz. However, the required energy for melting increases the needed input for 200 and 300 kHz.
Different temperature gradients result in different viscosity gradients in the steel. A certain change in viscosity (in x- and y-directions) is necessary to squeeze out oxides and other contaminants from the weld.

Simulations executed so far cover the course of events until the strip edges are welded together by the squeeze rolls. But the welding process continues beyond this point. After the rapid heating, a cooling takes place. The temperature vs. time during cooling is important with respect to the final weld quality. When the steel is heated, the grain growth accelerates above a certain temperature. The final steel structure in the weld depends on the transformation of these grains during the cooling. Later work could include examination of this part of the welding process.

CONCLUSIONS

With different frequencies applied, there are no dramatic differences in the shapes of the heated zones. At a welding speed of 14.6 m/min (48 f/min) the depth of the zone shows a slight tendency to increase when frequency is lowered from 300 to 100 kHz.

The local overheating of the edges and amount of molten material increase with frequency. It is clear that the energy needed for melting helps to stabilize the temperature in the edges.

The proximity effect is stronger for higher frequencies, but seems to come into account only a short distance ahead of the weld point.

The temperature gradient perpendicular to the weld line increases with higher frequency.

Can we now answer the question about the optimal frequency for medium- and thick-wall pipes? At least we have developed a tool for specific parameter studies on the welding process where there are many parameters affecting the weld quality.
There has been much focus on frequency in recent years. And indeed, we have done calculations for different frequencies so far. The results, however, indicate that the focus on the importance of frequency may have been exaggerated.

There is a growing desire to weld larger tube dimensions with induction welding which increases the necessary welder power rating compared with contact welding. A high welding frequency leads to a lower-power-to-volume ratio and a higher-cost-to-power ratio. A demand for greater throughput, therefore, may result in an increasing number of installations with high-power welders, lower welding frequencies and higher welding speeds. Consequently, studies of the influence of weld speed and Vee angle, among others, can be necessary to help fulfill these requirements.

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