

Numerical Simulation of Induction Assisted Hybrid Welding Processes

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Abstract

In order to weld heavy-walled metal sheets (16 mm and more) nowadays a hybrid process, that includes an electric arc and the laser beam, is frequently applied. Due to the high thermal conductivity of metals and the enormous temperature gradient between the laser-welded area and the not welded region around the bond, there is a big heat flow and the welded material is cooled down in very short time. This high decrease of temperature leads to decayed metallurgical qualities. In order to slow down the temperature drop an inductive process is appended to the hybrid welding device. Because of the high thickness of the metal sheets there are both an inductive preheating and an inductive postheating process added. To configure an optimal design for the inductors the numerical simulation is used and especially the heat generation of the welding process has to be included in a physical realistic way.

Introduction

Welding of heavy-walled metal sheets is a temperature critical process and thus it may lead to poor metallurgical qualities because of quickly falling temperatures. To slow down this temperature fall an induction system is added. The support by the induction system is divided in a preheating and a postheating process. The preheating part is applied to warm up the whole material and reduce the temperature gradient between the welding zone and the surrounding areas. After the welding by electric arc and laser beam there's a postheating process integrated that should minimize the temperature drop. To optimize the welding process and the parameters of the induction system a numerical simulation that uses the finite element method is deployed. For the induction process the software calculates the magnetic vector potential, the heat generation and consequently the temperature distribution. Therefore it shows the critical areas in the workpiece that has to be heated more or less. The welding process by the electric arc and the laser beam is highly transient and therefore it is very complicated to implement the heat sources of these two devices just by analyzing the power and the geometric dimensions. From the viewpoint of the simulation, the investigated process represents complex coupled problems marked by the combination of electromagnetic field, the temperature field generated by the induction system and the heat power density that is impressed by the welding sources.

1. Boundary Conditions

Some applications are constructed in this way that the inductor can only be positioned on one side of the metal sheet. In many cases also the welding devices can just be positioned on one side that is frequently the same side on which the inductor is located.

Because of the exponentially falling heat generation from the surface of the workpiece towards its core, what is typical for the induction process, it is hard to warm up the bottom side of the sheet properly. Also the mechanical space that inductor and the welding arrangement are requiring has to be kept in mind. The electromagnetic and thermal interaction between the electric arc respectively the laser beam and the induction system requires an area where only one of each warming device can be deployed.

After the sheets welding there is a buckling on the longitudinal seam as it is shown in Fig. 1 that may damage or even destroy the inductor. To avoid any unrequested secondary effects (i.e. electric contact between inductor and metal sheet) and structural injuries the air gap has to be raised. This calibration of course leads to a worse electric efficiency and therefore this application needs more power from the generator to reach the same temperature level.

The generator power is also high depending of the heading speed which is set by the operator and the length of the line inductor that is limited by the constructional dimensions. The available heating time can easily be calculated by the quotient of the inductor length and the heading speed.

There are also some specifications for the temperature levels that have to be adhered. In the moment when the electric arc is starting to warm up and melt the metal the highest temperature should not exceed a defined level. Material temperatures above this level are causing a badly behaving melting bath that can only be controlled hardly. The requirements for the temperatures during the postheating process are on the one hand a maximum temperature that is leveled below the temperature that causes oxide scales and on the other hand a minimum temperature level that is located above the tempering temperature to takes stresses out of the material and it also homogenizes the microstructure of the welded joint and the surrounding area. To reach a satisfying result the temperature at the root of the welding joint has to be hold above the tempering temperature for more than ten second even though the heat generation of the inductive postheating process can only be impressed for a few seconds. In spite of the low temperature gradient between the upper surface and the bottom of the metal sheet the embossed energy has to suffice for exceeding the prescribed limit of ten seconds.



Fig. 1. Buckling on a welded joint

2. The Model for the Numerical Simulation

A mathematical model considers the electromagnetic effect by the induction system and the heat generation by the hybrid welding source. The inductive part of the whole process consists of an inductor that is streamed by an imbedded current density and therefore the inductor forms a magnetic field that consequently leads to an exponentially falling heat generation from the surface of the workpiece towards its core. Equation (1) shows that the electromagnetic penetration depth δ is depending of some material properties and the frequency of the current in the inductor.

$$\delta = \frac{1}{\sqrt{\pi \mu \kappa f}} \quad (1)$$

Due to the fact that the material properties like the magnetic permeability and the electric conductivity can only be influenced by the temperature of the sheet the electromagnetic penetration depth has to be adjusted by the frequency of the inductors current. The primary aim consists of the temperature at the root of the welded joint. This temperature has to be held on a specific level for more than ten seconds and this has to be realized by the induction postheating process. To achieve this goal much energy has to be impressed on the bottom side of the metal sheet and therefore the penetration depth should be rather high. According to a high δ the frequency has to be very low. The disadvantage of a low frequency is justified in a poor electric efficiency and an elevated requirement to the capacitors in the oscillating circuit. Fig. 2 shows the effects of different frequencies to the electric efficiency and the temperature in the root of the knit line.

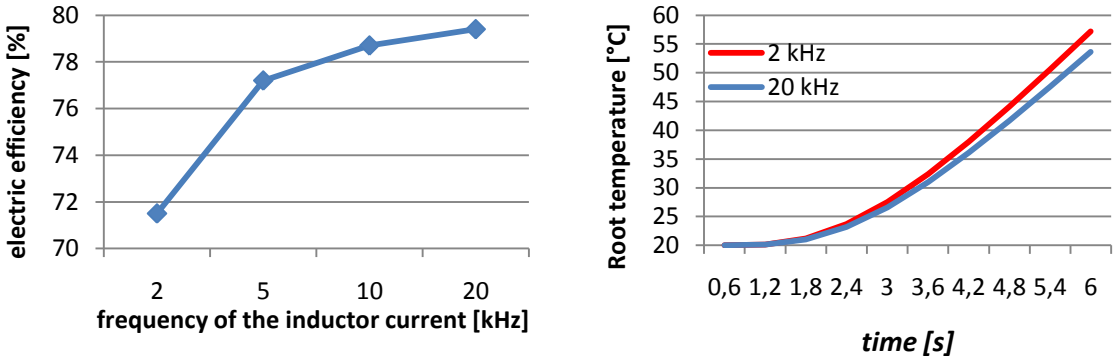


Fig. 2. Effect of different frequencies to efficiency and root-temperature

The results had been computed with a numerical model that includes a 16 mm-thick metal sheet and an inductor that is 30 mm wide, 10 mm high, its wall thickness is 2 mm and the air gap between the inductor and the metal sheets is 4 mm. For the right part of the picture the maximum temperature had been set to 200°C after a warming cycle of 6 seconds. It demonstrates the higher temperature at the root point at the 2 kHz-model and therefore the lower temperature difference that directly shows the more homogeneous temperature distribution in the workpiece.

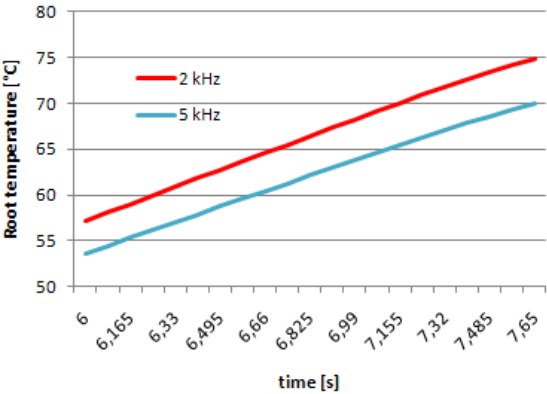


Fig. 3. Root temperatures during balancing period

Concerning to the limitation by the constructional dimensions of the electric arc device the balancing period possesses a length of 55mm that is equivalent with a time of 1.65 seconds at a heading speed of two meters per minute what is typical for the investigated welding operations. Fig. 3 displays the balancing period for the just specified examples.

The complete warming and welding process consists of many single steps like the two periods for induction warming, the electric arc process, the balancing periods and the laser

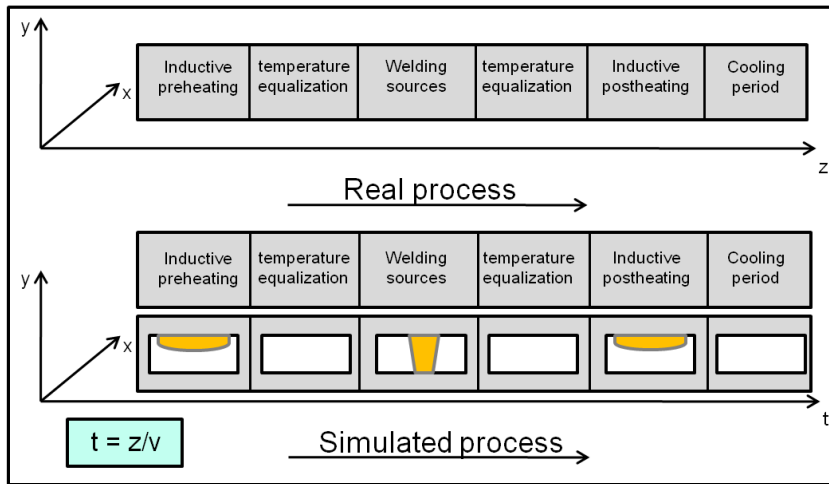


Fig. 4. Sequence of the process steps

beam process. Fig. 4 illustrates the sequence of the process steps and the opportunity to reduce the real 3D-problem to a time depending 2D-model by including the chart speed length of execution for every step.

The implementation of the high transient welding process is realized by imbedded heat generation densities in the metal sheet.

The mathematical base for these heat sources is set by jointly normally distributed half ellipsoid sources with set parameters. Equation (2) shows the function that defines the heat generation power per volume.

$$q_{vol}(x, y, z) = \frac{6\sqrt{3} \cdot P}{\pi\sqrt{\pi} \cdot x_{0,05} \cdot y_{0,05} \cdot z_{0,05}} \cdot \exp \left\{ -3 \left[\left(\frac{x}{x_{0,05}} \right)^2 + \left(\frac{y}{y_{0,05}} \right)^2 + \left(\frac{z}{z_{0,05}} \right)^2 \right] \right\} \quad (2)$$

Formerly used distributions of the heat sources at the surface of the workpiece are in this case with dipping welding procedures insufficient, because warmth is also generated inside the metal sheet. Furthermore the shape of the geometry of the welding zone can be expressed by the alternative with a half ellipsoid source much more realistic than with a constant heat source density. The chosen ellipsoid source also spares the raising of the thermal conductivity in the welded zone. None-ellipsoid models have to impress a raised thermal conductivity due to the convection of the liquid metal.

In reality there is a feed that has to be incorporated into the mathematical model.

Because of that the former half ellipsoid source is split up into two quarter ellipsoid sources with a different length in the direction of the feed. Fig. 5 shows the typical shape of the heat generation density in a process with feed. In this case the feed is adjusted in the x-direction. The origin of the Cartesian coordinate system is placed on the point with the highest heat generation. This is the location of the impact point of the laser beam respectively the electric arc.

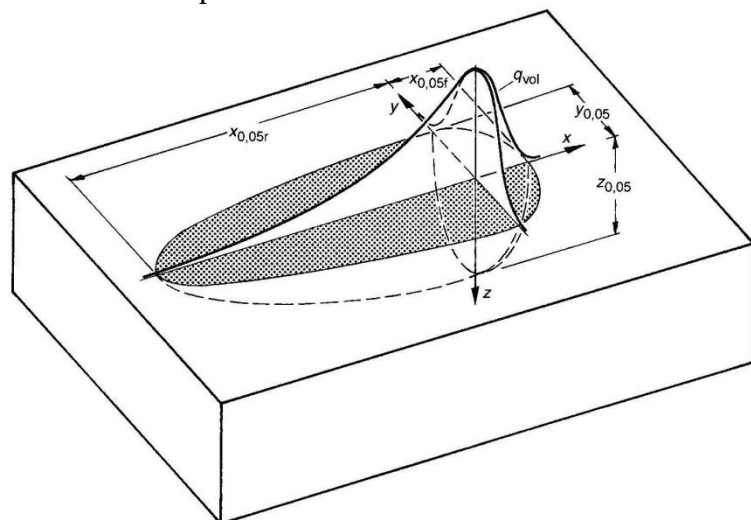


Fig. 5. Shape of two quarter ellipsoid sources

The dimensions $x_{0,05}$, $y_{0,05}$ and $z_{0,05}$ are characteristics of each welding application and can be determined by temperature measurements of experiments and by polished micrograph sections. The variable P describes the total power of the welding devices that can be

converted into heat. The length of the two x-dimensions in the front and the rear part of the welding zone has also to be identified by experiments. A typical scale is that the rear part is eight till ten times as high as the front fraction. This difference must be considered by a factor in each part of the equation. Equations (3) and (4) are demonstrating the influence of the division into two quarter ellipsoid sources.

$$q_{vol,f}(x, y, z) = f_f \frac{6\sqrt{3} \cdot P}{\pi\sqrt{\pi} \cdot x_{0,05f} \cdot y_{0,05} \cdot z_{0,05}} \cdot \exp\left\{-3\left[\left(\frac{x}{x_{0,05f}}\right)^2 + \left(\frac{y}{y_{0,05}}\right)^2 + \left(\frac{z}{z_{0,05}}\right)^2\right]\right\}, \quad (3)$$

$$q_{vol,r}(x, y, z) = f_r \frac{6\sqrt{3} \cdot P}{\pi\sqrt{\pi} \cdot x_{0,05r} \cdot y_{0,05} \cdot z_{0,05}} \cdot \exp\left\{-3\left[\left(\frac{x}{x_{0,05r}}\right)^2 + \left(\frac{y}{y_{0,05}}\right)^2 + \left(\frac{z}{z_{0,05}}\right)^2\right]\right\}. \quad (4)$$

It is important that the sum of the two included factors is $f_f + f_r = 2$ so that the complete power implementation is assured. As the whole period of the induction heating the ellipsoid sources for the welding implementation is realized in a 2D-model that respects the feed by adapting heading speed and the length of the source effect. In contrast to the induction where the origin of the electromagnetic field, that causes the heat generation density, is embossed, the region in that the heat generation is converted has to be implemented in each time step by a specifically source code. Fig. 6 shows the result of a numerical simulation of the warmth

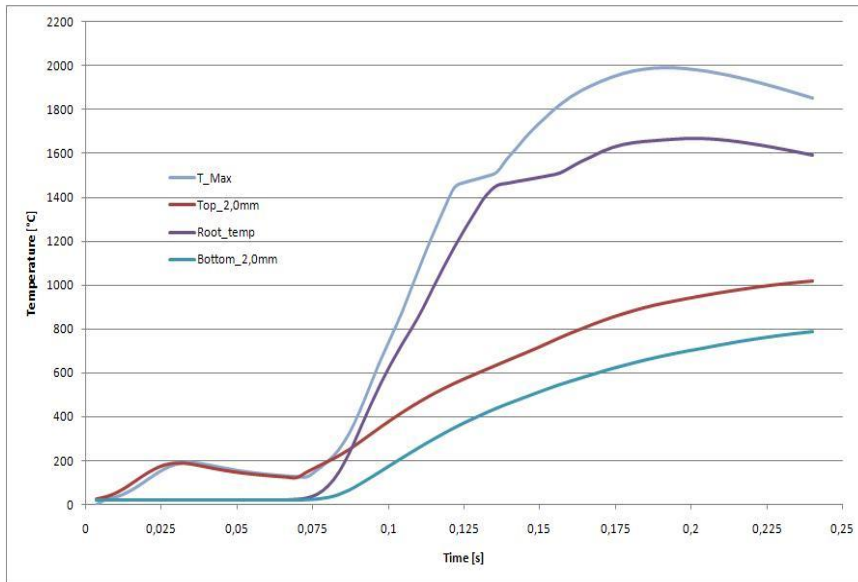


Fig. 6. Temperature development while welding process

development during the welding process. The four shown distributions are expressing the maximum temperature in the whole workpiece (T_Max), the warmth in a distance of 2 mm to the knitline on the inductor facing sur-face (Top_ 2,0 mm), the temperature in the root of the welded joint (Root_temp) and the heat development on the inductor averted surface in 2mm distance to the longitudinal seam (Bottom_2,0mm). The electric arc has got a plane and coincidental wide heat generation effect. The Top_2,0mm-characteristic shows the wide warming effect by the electric arc because of its rising in the fast part of the welding process. The temperature in the root doesn't increase before the laser beam is starting in the second part. The development of Bottom_2,0mm displays the non-deep-penetrating effect of the electric arc in the first fraction and the narrowness of the laser beam in the second part. There are no high increases of the temperature by reason that it is only warmed be thermal conductivity.

The size of the time steps during the period of welding has to be very small. The whole size of the welding devices effect is about 8 mm long and while this time the heat generation cycles the complete ellipsoid process with its very high increase in front of the origin and the little less but also very high decrease behind the point with the main heat

generation. A heading speed of two meters per second and a welding zone length of 8 mm (typical dimension in industrial processes) are entailing a time frame of 0.24 seconds that has to be split up finely to reflect the ellipsoid shape almost correctly. To get a realistic heat generation this time slot should be segmented in more than 96 parts what involves a step time of less than 2.5 milliseconds. Even if the time steps are that small there's a maximum switch from 54,5% to 66,8% of maximum heat generation that has to be approximated properly by the specific source code.

Conclusions

The paper presents results of numerical simulations of hybrid welding processes that are implemented by jointly normally distributed half ellipsoid sources with set parameters and that are also supported by induction pre- and postheating processes. Furthermore the half ellipsoid source should be split up into two quarter ellipsoid sources to impress the feed of welding processes in numerical simulations. Its operation mode is verified by comparisons with industrial trials and experimental data. The knowledge of the thermal performance during the supporting induction processes and the influence of the electric arc and the time-delayed laser beam are essentially benefits of this exploration. It also shows the opportunities and simultaneously the requirements of a physical correctly implementation of the high transient welding process with its heat generation effect in the interior of the workpiece. It is necessary to have a realistic temperature distribution after the welding process to configure the inductive postheating trial properly. The induction processes are added to influence the cooling-rates of the metal sheets and therefore to advance the material properties. By using the demonstrated procedures required tempering times and temperature profiles in consideration of a high efficiency can be determined.

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