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Modeling and optimization of induction assisted welding processes

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Abstract

Coming from automotive applications, high strength steel grades to be applied in lightweight construction are more and more required in many industrial sectors as construction, agricultural machinery or shipbuilding industry. However, fundamental metallurgical facts cause these steels to be relatively difficult to weld. This limitation in wider use of high strength steels can be overcome by the use of appropriate welding methods combined with induction heating. The report represents an overview of the progress in design and optimization of such induction heating systems with regard to their interaction with different welding sources.

Introduction

The presented investigations were performed in the frame of the European project INDUCWELD. In the frame of this project, the Institute of Electrotechnology (ETP) investigated and designed the induction heating systems for different welding techniques and applications. For this purpose, a special numerical model had been developed, which respects the mutual influence of welding and induction heating process and allows the modeling of the thermal behavior within the complete process. The paper presents the principles of process description, results of investigations performed on existing welding installations and their comparison with measurement data. Selected results of process optimization show further capabilities and functionality of presented strategy. Reducing the cooling rate, controlling the temperature level during the welding process (reducing the hardness), increasing the formability and toughness as well as increasing the efficiency of the welding processes (due to higher welding speed) are the main advantages of optimized induction heat treatment in welding processes.

1. Approach to the process-modeling

From the viewpoint of the simulation, the investigated process represents complicated coupled problem characterized by the interaction of electromagnetic field and temperature field. That is why a mathematical model of both physical fields has been created. Moreover, the influence of welding process itself has to be taken into account. Therefore, a methodology of implementation of laser energy has been developed based on experimental data.

The finite element model (developed using the commercial software package ANSYS) uses 2D approach to describe the temperature behavior of the welding process and respects the movement of the welding sources by their change in time. It carries out the thermal analysis of different welding procedures as well as the electromagnetic and thermal analysis of induction heating process for both plane-parallel (sheets) as well as axisymmetrical (rotational parts) arrangements. As a result the model provides the knowledge of time and space temperature distribution within the welded steel plates and allows herewith the optimization of the induction heating systems under actual process condition. Material properties used in the model are temperature dependent and ensure the correct behavior of the model in the whole temperature range (from ambient temperature to maximum temperature during the welding process). Laser, plasma or GMA impacts are included as two-dimensional fields of heat sources varying in time. Methods of their implementation, dimensions of the active weld area for different materials and thicknesses etc. have been determined using experimental results (Fig. 1 shows two examples of the actual shapes of the weld and its simplified implementations in the model). The microscopic effects in the welding process are not considered in the numerical model. These effects in such very small areas do not significantly affect the thermal behavior of the whole system, which should be investigated within this project. Modular structure of the model allows the simulation of all possible technological combinations of the welding process and possibilities of their induction heating support (pure welding process, post-heating, pre-heating etc.).

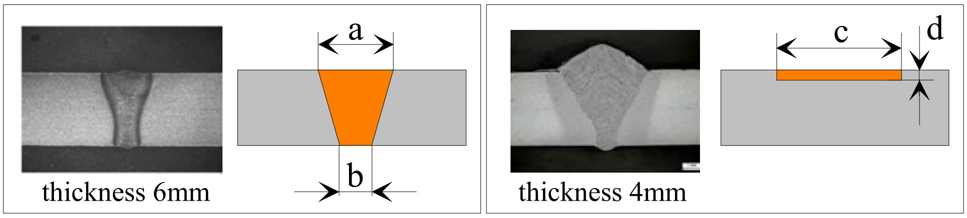

Fig. 1. Principles of laser and GMA welding energy implementation

2. Investigation on existing devices, comparison with measurement data

Several existing welding installations have been modeled in order to test and verify the capabilities of the numerical model. Different welding processes and configurations were considered to prove the accuracy and versatility of the model. The following part shows the selected examples of the results. Schematic description of investigated arrangement and the main process parameters are shown in the Fig. 2. Steel grade S690QL has been considered for simulation and experimental verification. First of all, in order to adjust the model with measurement, the time temperature distribution in the middle of welding seam has been observed on the upper steel side. This calculated temperature curve was compared to measurement data as can be seen in the Fig. 3. This comparison shows good agreement within the whole process. In the first part of the temperature curve, the temperature can not be correctly measured, because of hiding of pyrometer by inductor. In this case, the simulation offers the possibility to observe the temperature even at these inaccessible points.

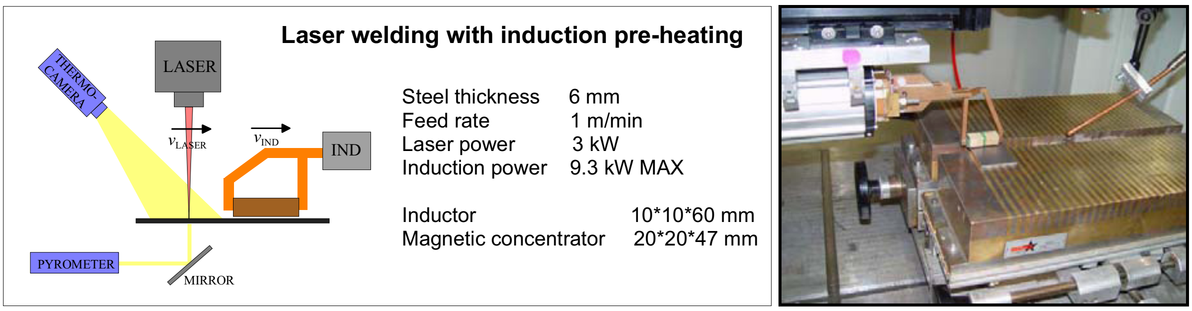

Fig. 2. Parameters of the investigated process and overview of the experimental installation (IWS Dresden)

It can be observed that the maximum temperature during the induction heating process appears already before the end of the coil - at the end of the magnetic field concentrator. It means that the actual value of temperature during induction heating is higher then the measurement shows.

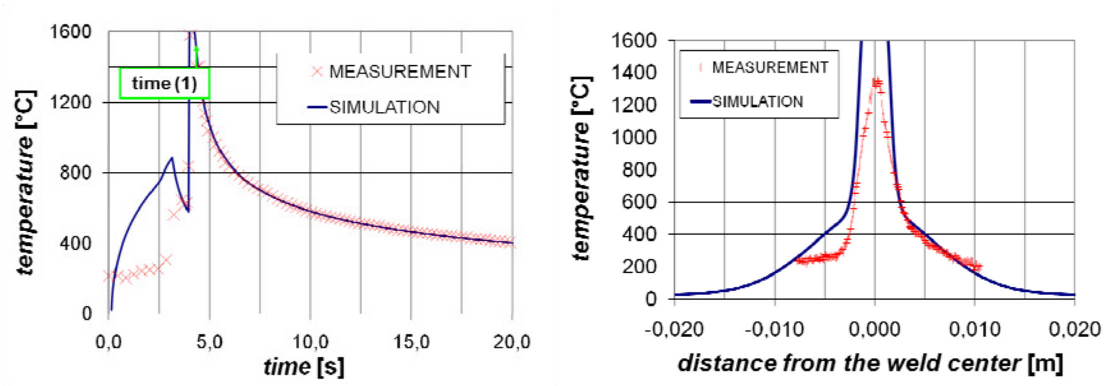

Fig. 3. Time-temperature distribution on the upper side of the weld and temperature profile on the upper side after the laser process for time (1)

2. Process optimization – flat geometries

Numerical model presented above has been used for design and optimization of different heating systems in order to ensure the defined improvements of high-strength steel welding methods. There are different requirements on such heating system depending on welding technology, work-piece geometry (sheets, massive parts etc.) and intended goal of heat treatment (reduction of temperature gradients, increase of welding depth etc.) which can be reached by various methods of heat treatment (pre-heating, post-heating). In any case, a lot of parameters and their influence have to be investigated depending on particular process to find an optimal design. Selected results and their effects on thermal behavior are presented in the next part.

Let us consider the arrangement shown in the Fig. 2. Influence of inductor length in the welding process (S690QL, sheets thickness of 6 mm) with integrated induction preheating is shown in the Fig. 4. Providing the constant feed rate of 1 m/min, various depth of preheated zone can be reached by variation of inductor length (see the temperature distribution on the root side).

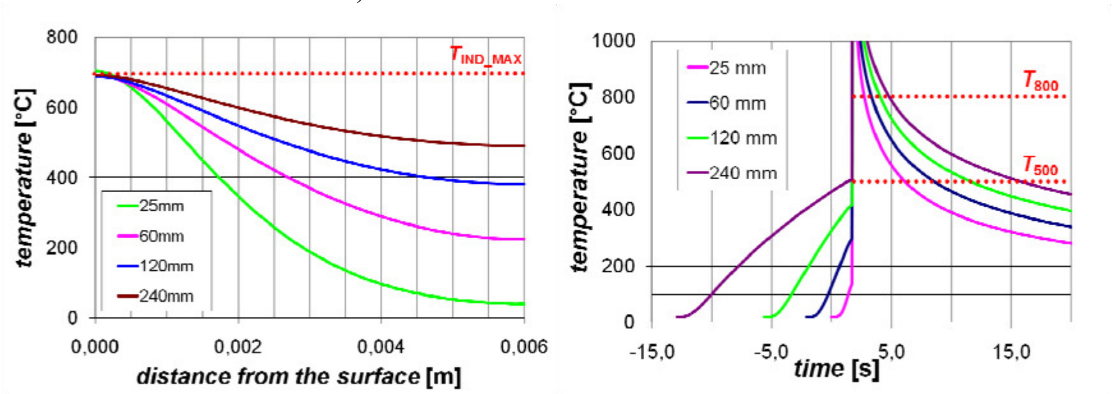

Fig. 4. Laser welding process with induction preheating: influence of the length of coil (left: temperature profile over the sheet thickness; right: time-temperature distribution on the root side of the weld)

Although the maximum surface temperature after induction heating remains unchanged (see Fig. 4, left) root side temperature increases due to thermal transfer by conduction through the welded sheets. Additionally, the cooling rate after laser process determining the final material structure ($t_{8/5}$ time) is significantly prolonged (see Fig. 4, right). This finally leads to reduction of thermal stresses in welded material and avoiding of residual tensile stresses which may result in material cracks. Having determined the temperature behavior of the complete system including both induction and laser part, an optimal length of inductor can be chosen. Additionally, for a stable welding process a suitable modification of inductor length can lead to increase of welding speed, reduction of laser power and accompanying energy and time savings. Optimization of other parameters of induction systems for flat geometries as e.g. cross-section of inductor or generator frequency has been performed by means of presented numerical model.

For thicker sheets (thickness from 12 mm up to 30 mm) a V-shaped and X-shaped weld preparation are used. Induction pre-heating by standard inductors leads in this case to overheating of upper surface part and non-uniform temperature distribution in the seam. Therefore, a new design of inductor for pre-heating has been developed. Distribution of magnetic field is modified due to an optimized copper profile and penetrates deeper into the air gap between the plates. Corresponding temperature distribution shows consequently a homogeneous temperature profile. Based on the parametrical studies, a new experimental inductor has been built (Fig. 5).

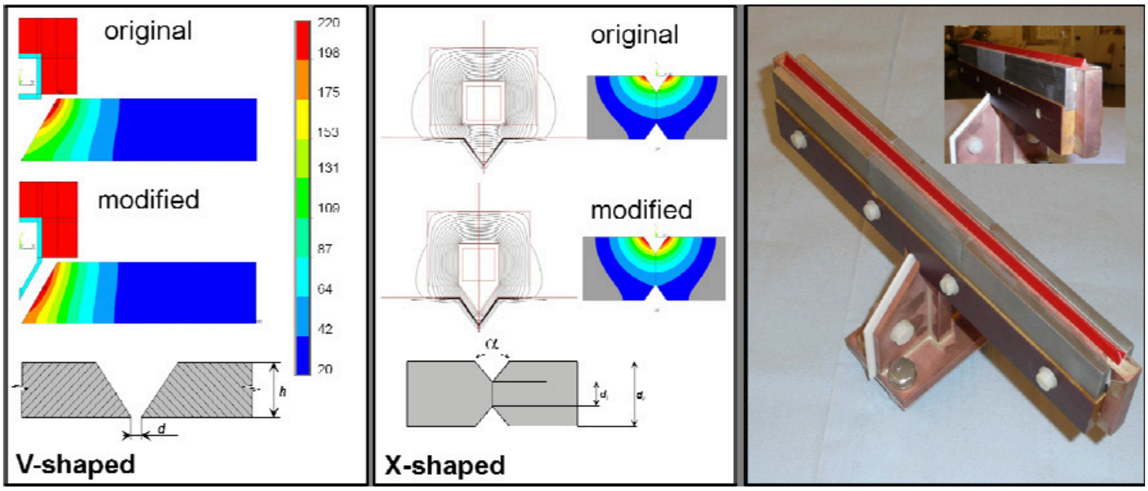

Fig. 5. Induction pre-heating: Influence of inductor geometry on temperature profile and photograph of the experimental inductor

2. Process optimization – rotational geometries

Welding process of a spindle made of hardenable steel with a sheet metal made of high strength construction steel has been selected as an application for demonstrating induction assisted welding of rotational geometries. A current standard procedure of complete tempering in an oven (to reach a sufficient welding temperature) can be replaced by partial induction pre-heating of the welding zone. This new approach allows a significant decrease of process and handling time and reduces the needed pre-heating energy. Selected demonstrator part and its simplified description for simulation purposes are shown in the Fig. 6. One turn inductor located close to the welding zone has been chosen for pre-heating of welding zone at the prescribed temperature. The geometry of the spindle has been simplified (the total mass of the work-piece has been kept) in order to accelerate the numerical simulation.

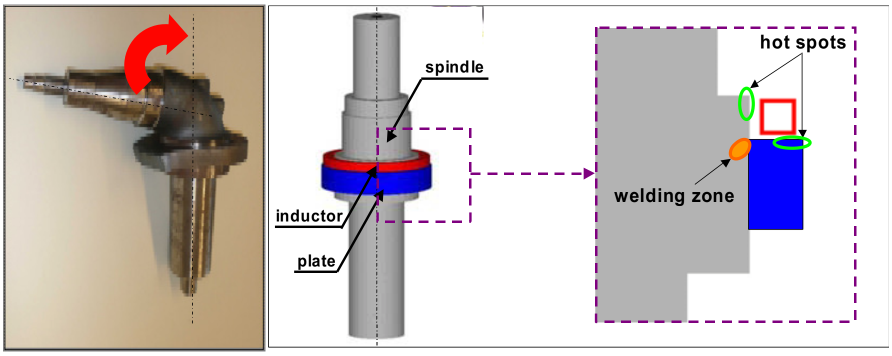

Fig. 6. Welded parts (produced by CNH Belgium N.V.) and schematic sketch of investigated welding arrangement

The aim of induction pre-heating is to reach the prescribed temperature in the welding zone as fast as possible. The maximum allowed temperature (600°C) should not be exceeded. The simulation gives the possibility to evaluate the temperature profile at each time moment of the pre-heating process and hereby optimize the design of inductor and the heating regime. Fig. 7 shows the temperature distribution in the spindle after 50 s and 100 s of pre-heating. It should be pointed out, that the maximum temperature does not appear in the welding zone itself. Having evaluated the distribution of magnetic field, the hot spots in the corners (shown in the Fig. 6) can be expected. Therefore, the temperature measurement which is usually used to control the induction heating process must respect this fact. The increasing size of pre-heated zone due to thermal conduction can be clearly observed for longer heating times. Having evaluated the temperature distribution, an optimal tempering time providing the required temperature profile in the welding zone can be also determined by help of this model.

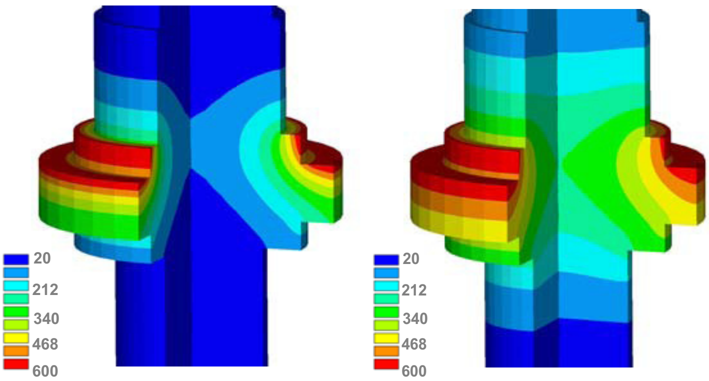

Fig. 7. Temperature distribution after 50 s (left) and after 100 s (right) of preheating

The time-temperature distribution in the welding zone for different heating times including the cooling phase after switching off the inductor (60 s) is shown in the Fig. 8. The longer the preheating time, the more uniform temperature in the welding zone can be achieved. This temperature distribution consequently influences the cooling rates after heating. As the welding process itself starts immediately after switching off the inductor, the cooling down in the welding zone influences the initial condition during the laser process. To avoid too fast decrease of temperature (and consequent variation of the weld depth) this part of time-temperature diagram must be carefully evaluated and can be easily investigated by means of presented model. Additionally, the simulation provides the information about influence of inductor position, needed generator power etc. and helps to find a suitable process configuration which will ensure the optimal pre-heating conditions.

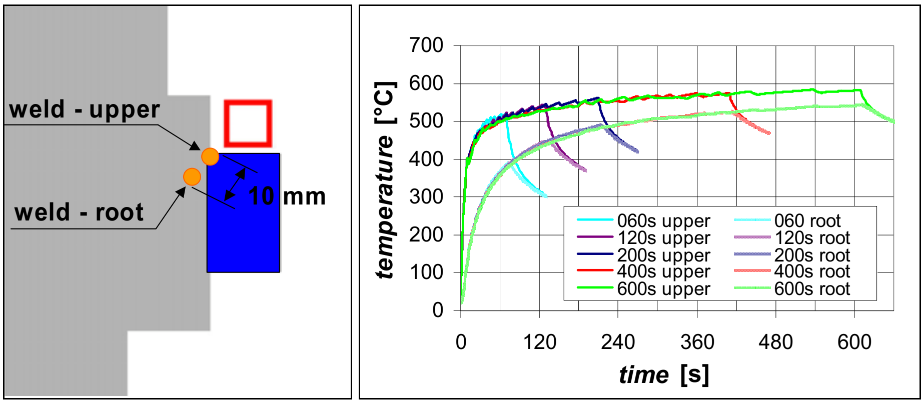

Fig. 8. Sketch of the arrangement with observed points in the welding zone (left); time-temperature distribution on the root and upper side of the weld for different pre-heating times (right)

Conclusions

The paper presents numerical simulation tool for description of thermal behavior of welding processes with integrated induction heating support. Its functionality is tested by comparison with experimental data and the results confirm its usability for design of such induction heating systems. Knowledge of thermal behavior during the whole process including cooling rates and thermal gradients in welded parts is the main advantage of this approach. Selected results of consequent optimization of heat treatment for both flat and rotational geometries are shown. Choice of the optimal parameters of inductor providing the required cooling rates can be done using the results of numerical simulation in the case of flat geometry. Simulations of the pre-heating process of selected rotational part have shown the thermal behavior during and after the pre-heating process. Appropriate tempering time providing the required temperature profile with maximum efficiency can be chosen using these results.

Acknowledgement

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