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Article

Verification of the welding heat source models in arc welding and hybrid plasma-MAG welding processes based on temperature field tests

Damian Rochalski [1], Dariusz Golański[1,*] and Jacek Szulc[2]

[1] Warsaw University of Technology; Poland
Damian Rochalski; damian.rochalski@gmail.com
[2] Supra Elco; Poland
Jacek Szulc; jacek.szulc@supraelco.waw.pl
* Correspondence: Dariusz Golański; dgol@wip.pw.edu.pl

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Abstract: Hybrid welding processes belong to a new group of welding varieties that most often combine two classic welding methods, such as laser welding with MIG/MAG welding or plasma welding with MAG welding. Modeling of welding stresses in this type of welding requires the definition of a new type of heat source model that combines a concentrated stream of energy with a classic heat source, which occurs in an electric arc. The paper presents the results of temperature field modeling in conventional MAG welding and hybrid plasma-MAG welding. In the first case, the heat source model described by Goldak was used, and in the second case, the Goldak model was combined with the developed rectangular heat source model with a homogeneous distribution. The temperature distributions obtained from the simulations were verified by spot temperature measurements during welding with thermocouples. A fairly good agreement of the numerical analysis results with the temperature measurements for MAG welding was obtained, while in the case of hybrid welding the discrepancies between the modeling and temperature measurements were greater. The results were discussed, indicating potential causes and factors influencing the obtained test results.

Keywords: modeling of welding (FEM); hybrid plasma-GMA method; temperature measurement

Introduction

One of the most important issues accompanying numerical modeling of welding processes is the selection of an appropriate welding model of the heat source. It has a decisive influence on the temperature field formed in the welded joint, which in turn affects a number of factors determining the quality of the obtained joint. In the literature, you can find descriptions of various welding models of heat sources, hence their correct selection for a given welding process is necessary to conduct a correct analysis [1÷3].

Currently, the most commonly used and recognized model of a welding heat source is the Goldak model, which is usually used in the modeling of conventional arc welding processes such as MIG/MAG, TIG or coated electrode welding [4]. Nevertheless, the development of new innovative welding methods forces the search for new models of heat sources, which will be able to better describe the temperature field distribution in the materials to be welded. Such methods include, among others hybrid welding, where the heat source is created by two interconnected sources, e.g. a laser beam + a classic electric arc (MAG method), or a plasma beam + a classic electric arc (MAG) [5÷7]. In such processes, the Goldak model or other previously known models are not able to take into account the effects of a concentrated heat source, such as a laser beam or a plasma stream, in cooperation with a classic heat source.

While in the literature on laser-GMA hybrid welding we can find quite a large number of examples of hybrid heat source models [8,9], in hybrid welding processes, which is much less common in industrial applications, modeling a hybrid heat source combining a flux electric arc plasma is still a big challenge due to the lack of description of welding heat sources that can be used in this type of hybrid processes. For this reason, an attempt to develop and describe a heat source model in hybrid welding is now an important and current research issue.

The article presents numerical modeling of two welding processes: conventional MAG method using the Goldak model to describe the welding heat source and hybrid plasma-MAG welding using the proposed hybrid heat source model. The developed hybrid model of the welding heat source was subjected to experimental verification based on the study of the temperature field during welding with the use of thermocouples. The conducted research also allowed to draw attention to the problems related to temperature measurements during the welding process.

Conventional MAG welding process

Arc welding MIG / MAG (GMA) processes are currently one of the most used in industry. This is mainly due to the possibility of their relatively easy automation or robotization, with low costs of additional materials and the multitude of welding energy sources available on the market. Computer modeling of this process is widely used, and in the literature, we can find many different models of heat sources [10÷12]. Their multitude results from the pursuit of the best possible representation of the actual temperature distribution during welding, which affects, for example, the distribution of welding residual stresses.

Despite the large number of variants of welding models of heat sources describing the MAG welding process, the modeling of the conventional welding process is in most cases based on the model proposed by Goldak [4], whose experimental verification has shown the best representation of the temperature distribution during welding. Moreover, this model is now the basic model in all commercial numerical analysis software for welding processes (SYSWELD, Simufact Welding).

In this work, modeling of welding heat sources was carried out in a program dedicated to performing numerical simulations with the finite element method (FEM) – LUSAS FEA 14.7. It is a general-purpose program, which, unlike specialist programs such as SYSWELD or Simufact Welding, has certain limitations in relation to the conditions that occur during welding. On the other hand, it allows for free shaping and definition of the heat source, which is an important factor when trying to model new processes or variants of welding methods.

The modeling of the MAG welding process and temperature measurements during welding with thermocouples allowed for a preliminary assessment of the suitability of the software used and the method of temperature measurement for the verification of the heat source model used. Goldak's model (Fig. 1) was implemented in the LUSAS FEA software on the basis of the equations describing the power density distribution in the anterior and posterior ellipse quarters [4]:

$$q_f(x,y,\xi) = \frac{6\sqrt{3}f_f Q}{abc_f\pi\sqrt{\pi}} \exp\left(\frac{-3x^2}{a^2}\right) \exp\left(\frac{-3y^2}{b^2}\right) \exp\left(\frac{-3\xi^2}{{c_f}^2}\right) \quad (1)$$

$$q_r(x,y,\xi) = \frac{6\sqrt{3}f_r Q}{abc_r\pi\sqrt{\pi}} \exp\left(\frac{-3x^2}{a^2}\right) \exp\left(\frac{-3y^2}{b^2}\right) \exp\left(\frac{-3\xi^2}{{c_r}^2}\right) \quad (2)$$

where:
q_f – heat source power per unit volume in front of the electrode axis
q_r – heat source power per unit volume behind the electrode axis
$Q = \eta UI$ – total power of the heat source at current I, voltage U and efficiency η

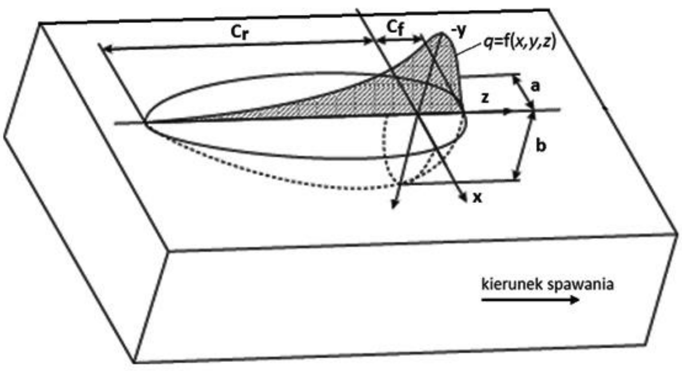


Fig. 1. Geometric parameters described by the double ellipsoidal model of the welding heat source according to Goldak

Model of a MAG welded joint

The parameters of the heat source used according to the Goldak model were selected on the basis of the previously conducted experimental tests of the MAG welding process. In the prepared model of butt-welded two steel plates with dimensions of 100 x 100 x 3 mm, the boundary conditions in the form of heat exchange with the environment by convection were taken into account (cooling the heated plate in the air, heat transfer from the bottom to the lower plate on which the welded plate was attached). A very important aspect in the description of the numerical model are thermal properties of welded materials (thermal conductivity, specific heat, density), which were selected for pure iron on the basis of [13]. These data take into account the variation in material properties with temperature, which partially takes into account the phase changes that occur.

Figure 2 shows the determined temperature distribution at a selected time moment for the Goldak model when welding steel sheets with the MAG method. The red color shows the area of the liquid pool. A much larger temperature gradient is clearly visible in front of the heat source than behind it. There is also a characteristic "tail" behind the source, which results from the direction and speed of welding.

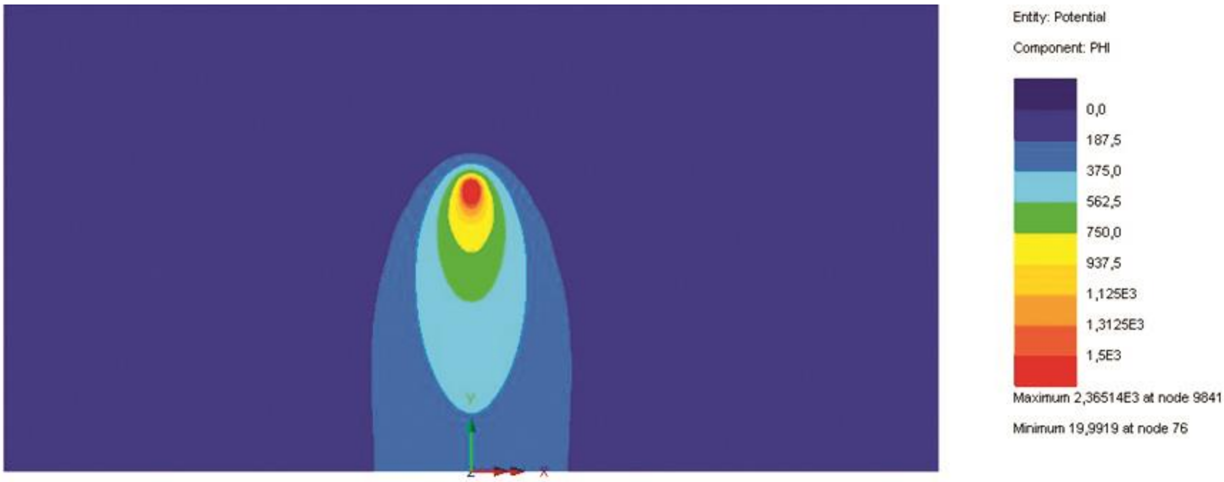


Fig. 2. The temperature field at the selected moment of time for the Goldak model determined for the MAG butt welding of plates

By analyzing the temperature field in the transverse and longitudinal sections (Fig. 3), it can be concluded that for the modeled welding parameters, full penetration is not obtained, because the linear energy of welding is too low. This has been confirmed during experimental studies. Likewise, a greater temperature gradient is visible in the longitudinal section of the joint in front of the liquid pool than behind it.

Fig. 3. Temperature distribution in the cross-section of the joint (top) and in the longitudinal section (bottom) for the Goldak model when welding sheets with the MAG method

Temperature measurements during the experimental MAG welding test

After the numerical analysis of the temperature field when welding two sheets with the MAG method, the constructed model of the welded joint was verified with the model of the heat source according to Goldak. The experimental tests were carried out on a robotic stand, adapted to MAG welding. Test plates made of S235 structural steel with dimensions of 100 mm x 100 mm and a thickness of 3 mm were used. Figure 4 shows a robotic station for MAG welding, which is equipped with a measuring system for recording the temperature during the butt welding process of two sheets.

It consists of a pyrometer and a meter to which thermocouples of type K are connected. A very important aspect influencing the quality of temperature recording with the use of thermocouples is the method of their connection with the tested material. The work [14] showed that it is possible to obtain a higher recorded temperature when using the surface connection of the thermocouple with the tested surface.

This is due to the much smaller volume of the thermocouple joint, which in turn results in lower measurement inertia. Therefore, as part of the measurements, the surface fixing of the thermocouple tip to the sheet surface was also used by welding it to the welded sheet with a special micro-welding machine.

Fig. 4. Robotized station for MAG welding

K-type thermocouples with a diameter of 0.4 mm and 1 mm were used for the tests. They were combined with the four-channel TM9017SD LUTRON meter. Figure 5 shows four welded thermocouples, mounted at different distances from the weld axis, respectively 2, 5, 8 and 10 mm.

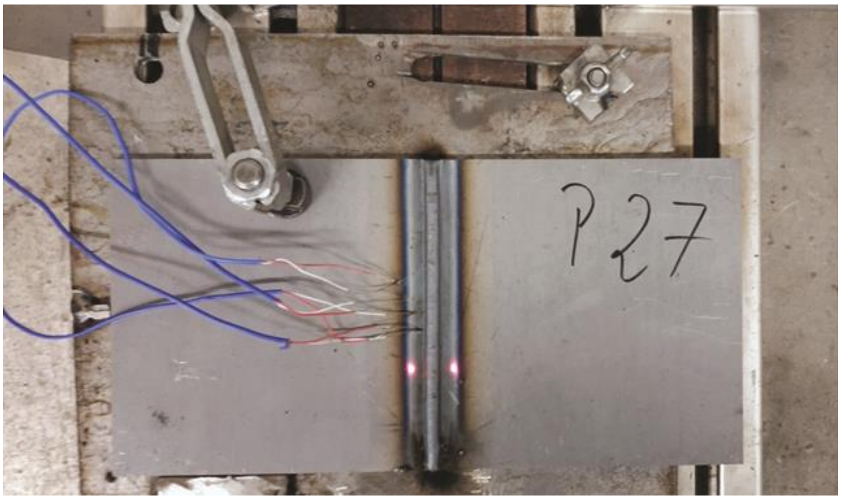


Fig. 5. View of the thermocouples attached to the test sheet after the MAG butt welding test

In addition, during the tests, the temperature was recorded using the TP10 pyrometer (visible spot in Fig. 5), but the results obtained from these measurements are only illustrative and are less reliable than the measurement with the use of a thermocouple, because the area from which the pyrometer reads the average data has approximately the shape of a circle with a diameter of 18 mm. Moreover, the necessity to enter the value of the appropriate emissivity factor into the pyrometer and the strong radiation occurring during the welding process significantly increase the inaccuracy of the results obtained in this way.

The preliminary temperature measurements carried out during the welding of sheets with the MAG method were to determine the effect of the thermocouple diameter on the maximum recorded temperature. The tests were carried out for two diameters of the thermocouple, 0.4 mm and 1 mm. The obtained results are predictable, the larger diameter of the thermocouple leads to the creation of a thermocouple with a larger volume. As a result of the heat source, which is a moving electric arc, a thermocouple with a larger volume (1 mm diameter) has greater measurement inertia and the recorded temperature is much lower than for a thinner thermocouple with a diameter of 0.4 mm (Fig. 6).

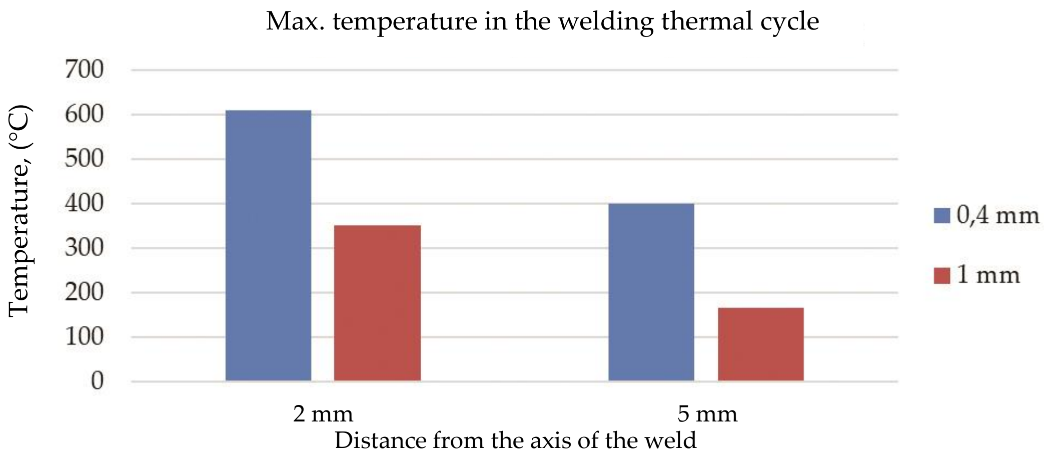


Fig. 6. Graphs of the dependence between the diameter of the thermocouple (0.4 and 1 mm) and the maximum recorded temperature in the welding cycle

A study was also carried out to check the repeatability of the measurements carried out. The temperature during welding (thermal cycle) was measured for four thermocouples (T1-T4) with a diameter of 0.4 mm, spaced from the weld axis by the same distance equal to 5 mm. The obtained results are shown in Figure 7. It can be seen that the shape of the recorded thermal cycles and the maximum recorded temperature are almost identical for all four thermocouples. Only a slight shift in time is visible, which results from a certain distance between the measurement points. These studies prove that the adopted methodology of temperature measurement with thermocouples is characterized by a very high repeatability, which affects the reliability of the obtained results.

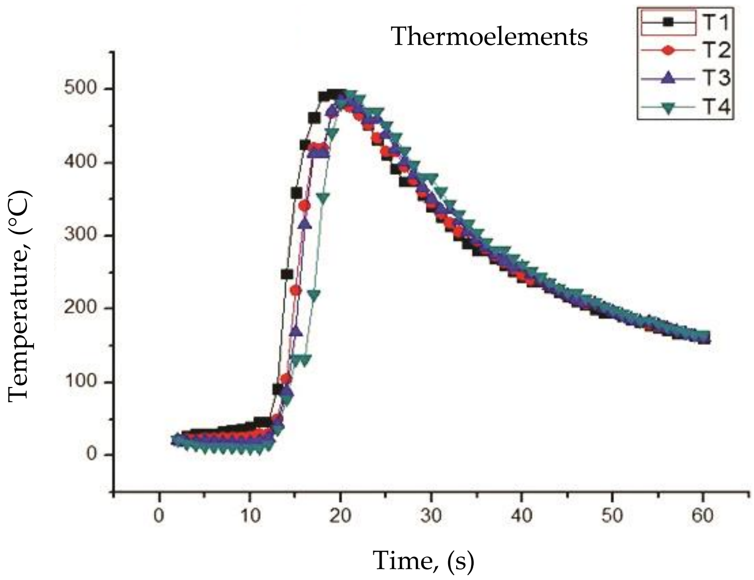


Fig. 7. Thermal cycle recorded by four thermocouples mounted 5 mm from the weld axis

Temperature measurements during the experimental MAG welding test

On the basis of the conducted experimental tests, thermal cycles were obtained for selected measuring points on the surface of the welded sheets. The obtained results were compared on a common graph with the results obtained by FEM modeling (Fig. 8).

Some dependence can be seen from the graphs in Figure 8. Both the shape of these charts, the heating rate and the cooling patterns are similar to each other. For points distant from the weld axis by 8 and 10 mm, the maximum cycle temperature differs from the value calculated in the modeling by no more than 50 °C. For a measuring point at a distance of 5 mm from the weld axis, this value increases to approx. 100 °C. On the other hand, for the point closest to the weld axis (2 mm), a much larger discrepancy in the maximum temperature range between the measurement and calculations is visible. Such a difference may be due to a certain inertia of the thermocouple junction, as higher temperatures require longer time to heat them up. Despite this, it can be concluded that the verification of the calculation results indicates the correctness of the use of the Goldak heat source model for numerical analysis of the MAG arc welding method.

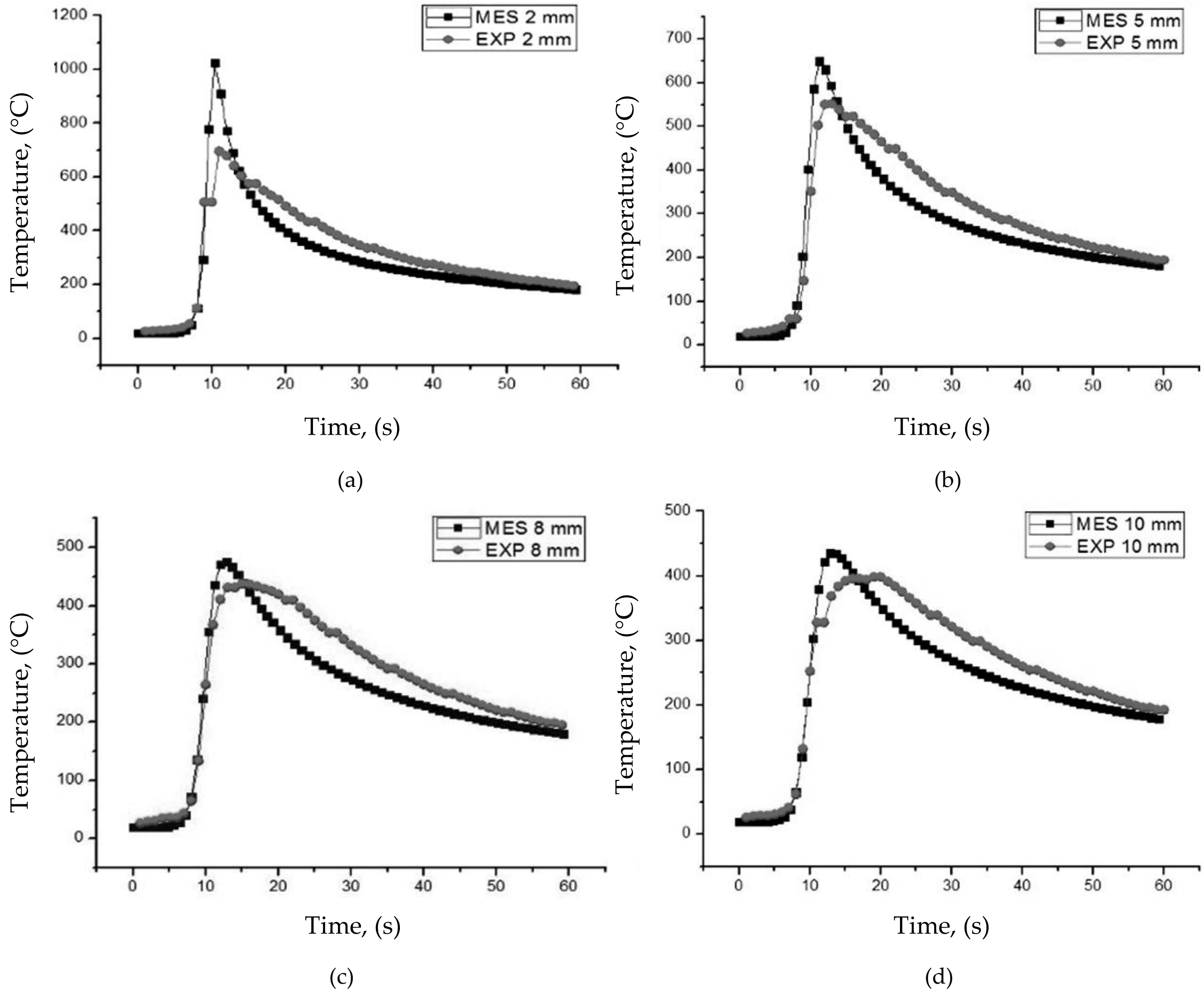


Fig. 8. Comparison of thermal cycles obtained from modeling with the finite element method (FEM) and measurements with thermocouples (EXP) for measuring points at different distances from the weld axis: a) 2 mm, b) 5 mm, c) 8 mm, d) 10 mm

Plasma-MAG hybrid welding

The constant development of many industries, visible in recent years, requires the use of high-performance welding methods based on laser or plasma techniques. Increasingly, the use of hybrid welding processes in many areas of the industry can be observed. The plasma-MAG hybrid welding process can be an attractive alternative to the laser-based hybrid process. Its main advantage is significantly lower costs of purchasing and operating dedicated devices while maintaining similar performance [15, 16].

In the plasma-MAG hybrid welding process, two electric arcs occur simultaneously [17,18]. The first is high-energy plasma, which is designed to open the steam channel. The plasma energy is so high that some of the material begins to evaporate immediately. The plasma arc transfers heat to the material mainly by bombarding the anode with the electrons and changes the kinetic energy of the electrons into thermal energy as a result of collisions [19,20]. The second arc that follows at a constant short distance from the plasma arc is a standard MAG welding arc, the main feature of which is conductivity.

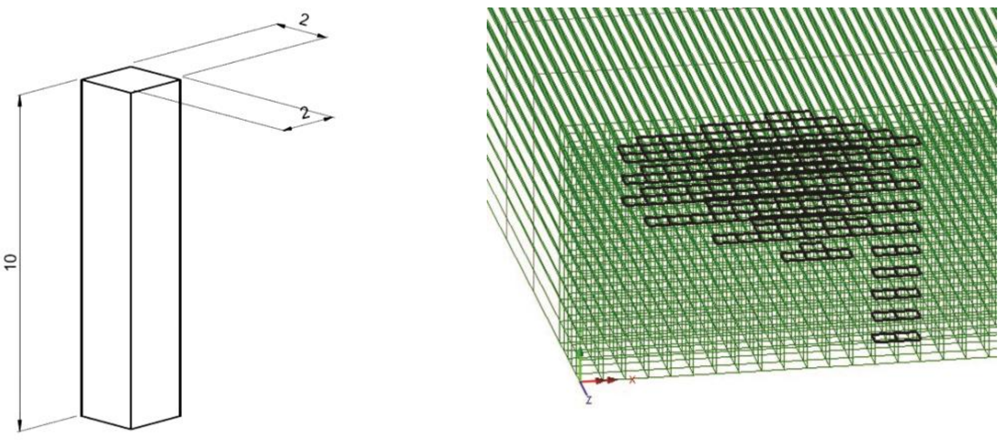
Numerical modeling of the temperature field in plasma-MAG hybrid welding

The two heat sources present in the plasma-MAG hybrid welding process transfer energy to the material differently, therefore the calculation model of such a source should also reflect these differences. The paper proposes a heat source model resulting from the combination of the Goldak model with the developed cuboidal model, which approximates a concentrated heat source, which is a high-energy plasma. The cuboidal model, unlike the Goldak model, is a model with a homogeneous distribution. The parameters of the hybrid model and the power of the heat source were selected on the basis of an experimental test of hybrid welding of S700MC sheets [17].

A numerical model of a welded joint of two sheets 350x150 mm with a thickness of 10 mm made of thermomechanical steel S700MC was built in the LUSAS FEA program, which, as research has shown, is less degraded under the influence of the thermal cycle of plasma-MAG hybrid welding compared to conventional arc welding processes [18,20-23].

In the case of two heat source models, separate values of heat input of 8.65 kW for the classic MAG source and 6.3 kW for the adopted plasma model of the source in the form of a cuboid with a homogeneous distribution were adopted (Fig. 9). The remaining assumptions (boundary conditions) were identical to those in the simulation of the conventional MAG process.

Figure 10 shows the results of the numerical analysis carried out in the form of a temperature field during the hybrid welding process obtained at a specific point in time (the source is located in the middle of the plate length). When analyzing the longitudinal cross-section of the weld, it is clearly visible that in its front part, the area of the presence of the liquid pool occurs over the entire thickness of the material, which may indicate that a full penetration has been obtained and is related to the operation of a highly concentrated plasma arc ensuring deep penetration. Further on, this area is clearly shallower. This is due to the fact that at the beginning, a concentrated plasma arc acts on the material to be welded, followed by the classic welding arc that occurs in the MAG method. Both arcs simultaneously follow a short distance from each other due to the construction of the plasma + MAG hybrid welding head, which was also taken into account in the numerical analysis.



(a) (b)

Fig. 9. The heat source model adopted for the plasma part of the hybrid welding process (a) and the graphic representation of the entire hybrid heat source model against the background of the finite element mesh (b)

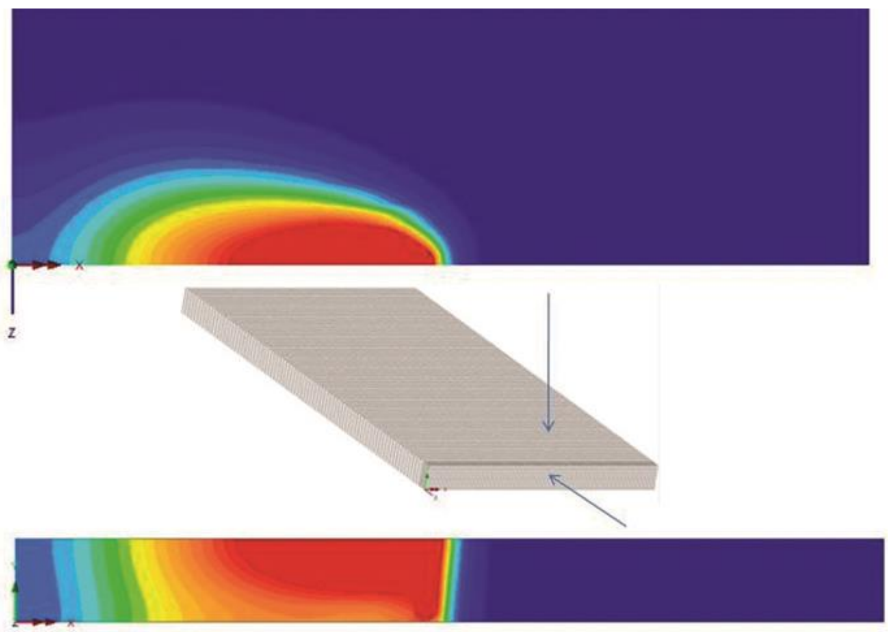


Fig. 10. Temperature field during the plasma-MAG hybrid welding process (top view and in longitudinal section)

Temperature measurements during the experimental welding with the hybrid plasma-MAG method

Experimental tests of temperature measurement were carried out for the plasma-MAG hybrid welding process on a KUKA KR 16-2f industrial robot station using the PLT Hybrid Super-MIG system hybrid head and the same measuring instruments as for temperature measurements in conventional MAG welding. The test stand used, and the test sheets made of S700MC steel mounted in the welding equipment with thermocouples welded to their surface are shown in Figure 11.

(a) (b)

Fig. 11. Stand for experimental tests of the plasma-MAG hybrid welding process with temperature registration using thermocouples: a) hybrid welding station with a KUKA KR 16-2f robot, b) welded joint with fixed thermocouples

When modeling the temperature field in plasma + MAG hybrid welding, a good verification of the model of the adopted heat source is a comparison of the obtained shape of the weld with the actual image obtained from metallographic tests. The weld obtained in the plasma-MAG welding process usually has a quite characteristic shape resembling a chalice, which is the result of the interaction of two different heat sources: one generating a deep fusion (plasma) and the other aimed at filling the groove (arc in the MAG method). Figure 12 shows a comparison of the actual shape of the plasma-MAG hybrid weld (right) with the image of the temperature field in which the melting point of the welded material was exceeded, i.e. in the area of the weld.

Fig. 12. Comparison of the weld shape in the cross-section of the hybrid-welded joint according to the results of the temperature distribution (left) and the metallographic tests of the weld (right)

It should be noted that the obtained shapes of the joint are very similar. Parameters such as the width of the joint in the face, the root and the height of the base of the chalice, which define its shape, are very similar to each other. This type of comparison is one of the first methods of assessing the accuracy of the constructed welding model of a heat source, which has a decisive influence on the size and distribution of the temperature field in the welded materials. The presented direct comparison of the cross-sectional structure of the welded joint with the numerically calculated one shows that the constructed hybrid model of the plasma-MAG welding heat source reflects the shape of the weld to a fairly good degree.

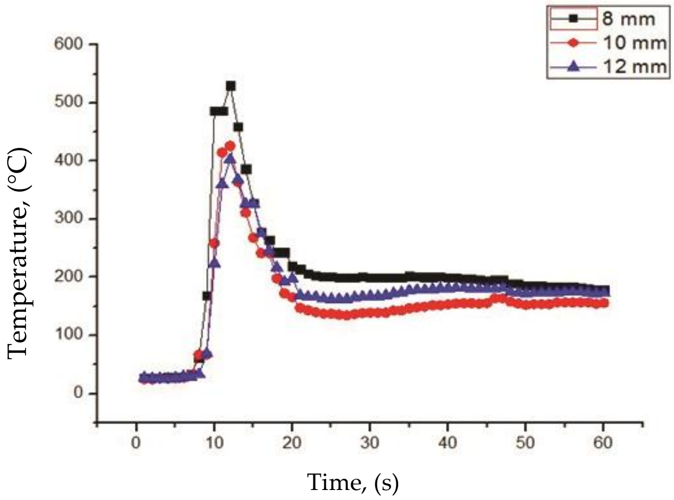


Fig. 13. The thermal cycle obtained during the experimental tests of plasma-MAG hybrid welding recorded for points located 8, 10 and 12 mm from the weld axis

Subsequently, temperature measurements were carried out during plasma-GMA hybrid welding with the use of thermocouples welded to the surface of the sheet at different distances from the weld axis (8, 10, 12 mm). Attempts to record the temperature at distances closer to the weld axis were unsuccessful in the form of damage to the thermocouple during welding. As a result of the temperature measurements carried out with the use of K-type thermocouples with a diameter of 0.4 mm, interesting thermal cycle distributions were obtained, which differ noticeably from the thermal cycle observed during the conventional MAG welding process (Fig. 13). The temperature rise phase is similar to the MAG process, while the shape of the cooling curve is slightly different. This is due to the heat source used, different thickness of the sheets, but also to the conditions in which the test joint was made. Moreover, after a fairly rapid decrease in temperature to a value below 200 °C, its minimal increase is observed, which may result from the copper pad used in the hybrid welding process, on which the test joint was welded.

Verification of the plasma-MAG hybrid welding model

Figure 14 shows a comparison of the results of numerical calculations and temperature measurements in hybrid welding with a thermocouple at a point 10 mm away from the weld axis. You can see a rapid increase in temperature to the maximum value, which in the case of measurement is about 200 °C lower than the value calculated as a result of numerical modeling of the hybrid welding process.

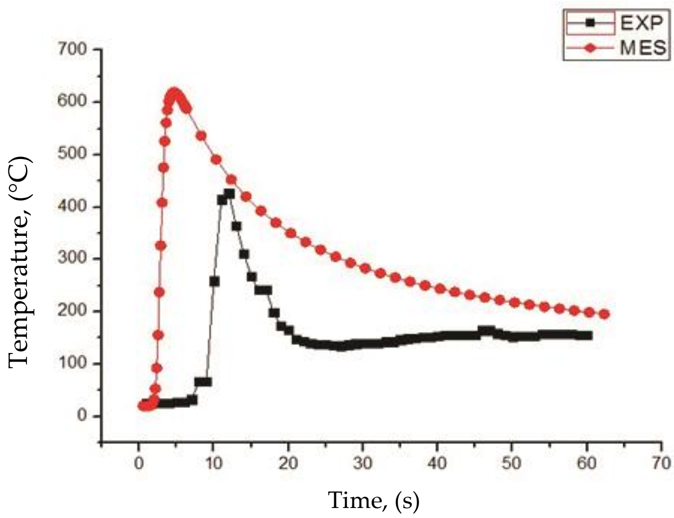


Fig. 14. Comparison of thermal cycles obtained by the finite element method (FEM) and experimentally (EXP) for a point 10 mm away from the weld axis

In the area of the cooling curve, the numerical model shows a milder character of the temperature drop than it results from the measurement, where, additionally, a slight increase in temperature is visible after a rapid decrease to approx. 150 °C. The inertia of the thermocouples used at high welding speed (1 m/min) is an important factor affecting the lower recorded maximum cycle temperature. Similar relationships were observed for the other two fixed thermocouples.

Conclusions

As a result of the conducted research, the classic model of a welding heat source (Goldak) was verified on the basis of tests of the temperature field when welding a butt joint using the MAG method. Measurements of thermal cycles with the use of thermocouples are very demanding, because there are a large number of factors affecting the obtained result (including the diameter of the thermocouple, the method of connecting the thermocouple with the welded material, measurement inertia). The encountered difficulties result mainly from the very high dynamics of the welding process and the wide range of temperatures, from ambient temperature to over 1500 °C. The obtained shape of the weld as a result of numerical calculations using the proposed model of a hybrid heat source shows quite good agreement with the actual image of the shape of the weld's macrostructure. The conducted tests of the temperature field during hybrid welding showed some discrepancies in the recorded thermal cycle, which are the result of both simplifications in the calculation model and a number of factors accompanying temperature measurements with thermocouples.

The published results refer to measurements carried out at the stage of preliminary tests of the temperature field for the plasma-GMA hybrid welding process. The obtained information will allow for the modification of both the calculation model of the hybrid heat source model and the refinement of temperature measurement procedures in relation to the high-speed welding process as in the case of the hybrid plasma-MAG method, which should enable better verification of the developed model of a hybrid heat source on the basis of research on thermal cycles.

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