INFLUENCE AND CHOICE OF HEAT TRANSFER COEFFICIENT BY WELDING SIMULATIONS OF TEMPERATURE FIELDS

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Abstract

Welding is a special process, that is carried out in a very short time interval with a small melting area and non-linear dependences. Consequently it is rather difficult to describe this process. The computations of temperature fields are based on thermal-physical data given by the Fourier differential equation and on the temperature dependence of the coefficient of the heat transfer into the environment. The heat transfer coefficient is an example of how difficult it is to acquire quality input data for simulation computation. It changes depending on the type of plane: vertical, horizontal or inclined angle-wise. It also matters if it is an upper surface of a plate or a lower surface of a plate, because the difference can be up to 30%. Simulations in the Sysweld programme will show how different types of the coefficient of heat transfer into the environment can influence the overall simulation computation result.

1 Introduction

Welding simulations of temperature fields are very difficult to achieve. The reason is mainly due to the non-stationary temperature field and high temperature gradient. Simulations of temperature fields are computed on Furrier´s differential formula base. For calculations it is therefore necessary to acquire the temperature dependence of the heat conductivity coefficient, specifically heat and density.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c \cdot \rho}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = a\nabla^2 T \, , \tag{1}$$

T	- Temperature	(K),
t	- Time	(s),
x, y, z	- Point coordinates	(m),
a	- Thermal diffusivity coefficient	$(m^2 \cdot s^{-1})$,
λ	- Heat conductivity coefficient	$(W \cdot m^{-1} \cdot K^{-1})$,
c	- Specific heat	$(J \cdot kg^{-1} \cdot K^{-1})$,
ρ	- Density	$(kg \cdot m^{-3})$.

At welding simulations heat source is moving and therefore temperature is both function of coordinates and also function of time. Resulting is non-stationary temperature field. Nonlinearities consequent with using Furrier’s differential formula and are given by partial derivations of temperature according individual coordinates, when each partial derivation determinates temperature gradient in the relevant axis direction.

Calculation of temperature fields by Sysweld programme by means of Furrier´s differential formula is based on heat source mathematical definition, represented by thermal flow density into material.

For the simulation computations so-called double-ellipsoidal heat source described by equations (2) and (3) is used. Source location ξ is expressed by equation (4). The efficiency of the transfer of heat into basic material is given by used welding method.

$$q(x,y,\xi)=\frac{6\cdot\sqrt{3}\cdot f_1\cdot Q}{a\cdot b\cdot c\cdot \pi\cdot\sqrt{\pi}}\cdot e^{\frac{-KXx^2}{a^2}}\cdot e^{\frac{-KYy^2}{b^2}}\cdot e^{\frac{-KZ\xi^2}{c^2}}, \tag{2}$$

$$q(x,y,\xi)=\frac{6\cdot\sqrt{3}\cdot f_2\cdot Q}{a\cdot b\cdot d\cdot \pi\cdot\sqrt{\pi}}\cdot e^{\frac{-KXx^2}{a^2}}\cdot e^{\frac{-KYy^2}{b^2}}\cdot e^{\frac{-KZ\xi^2}{d^2}}, \tag{3}$$

$$\xi = z_k - v(\tau - t) \tag{4}$$

$q(x,y,\xi)$ - Thermal flow density into the material $\left(W\cdot m^{-3}\right)$

Q - Total source power $Q = U\cdot I\cdot\eta$ (W)

a, b, c, d - Parameters of the melting area (m)

ξ - Source location in dependence on the welding time (m)

x, y, z - Point coordinates (m)

f_1, f_2 - Constants which influence energy flow intensity into the material $(-)$

τ - Total welding time (s)

t - Immediate welding time (s)

v - Welding rate $\left(m\cdot s^{-1}\right)$

z_k - Z axes coordinate when concluding welding (m)

Equations (2) and (3) are modified with the help of coefficients *KX, KY, KZ* so that the weld pool shape, given by simulation, corresponds with parameters measured under experimental testing.

Another thermal-physical quantity which influences the temperature fields by welding computations is the heat transfer by convection within the weld pool, which is expressed by Peclet´s number for heat transfer. Describing this quantity is extremely difficult. In one way it is dependent on applied welding technology, but it is also responsive to the welding efficiency and welding rate. With the classical welding technologies like (111, 131, 135, 141, 311) it is markedly evident up to welding rates of 0,92 m.min-1. Heat transfer influence is also possible to compensate for the mathematical description of the heat source modification.

The last heat transfer coefficient which also influences the temperature fields is the heat transfer coefficient to the surroundings. The temperature dependence determination of this quantity is important not only for the space geometry of welded parts, but also for setting conditions in welding surroundings. This submission deals with the heat transfer influence on the resulting temperature fields by simulation computations of the temperature fields in the Sysweld programme.

2 Heat transfer coefficient to the surroundings

Heat sharing between the solid wall and the fluid (during welding simulations posed by the surroundings) is very difficult. During welding heat sharing is partly evident to the surroundings by convection, but also (at high temperatures) by radiation heat sharing. For the temperature dependence detection of the heat transfer coefficient the convection heat sharing values are also important, as are radiation heat sharing values. The advantage is that the heat transfer coefficient does not depend on the welded material type so it depends only on the surface temperature of the welded part and the surrounding temperature.

2.1 Heat transfer by convection

During convection heat sharing it is necessary to distinguish whether it concerns the laminar or turbulent self-convection. This is determined by the temperature gradient size between the surface of the welded part and the surrounding environment. If the difference is lower than 15°C, it refers to the laminar convection, in the opposite case we refer to turbulent convection.

Another important criterion is the spatially directed area for which the convection heat transfer is computed. This is to say, whether the surface is vertical, horizontal, or a surface which is sloping on an angle. For the horizontal or sloping surface it is important to determine, whether it refers to the upper or lower surface of the plate. In the case of the lower plate surface it refers to the specific convection and the heat transfer coefficient will be about 30% lower than for the upper surface.

It is possible (on the basis of theoretical computation) to express heat transfer for all natural convection types with the help of the dimensionless numbers. Nuselt´s number (for heat transfer), Prandtl´s number (defines the physical constant of the fluids which influence convection) and Grashof´s number (for natural convection). In Tab. 1 temperature dependence of the convection heat transfer coefficient is computed.

Tab.1 Heat transfer by convection

Temp. [°C]	**20**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
α [W.m^{-2}.K^{-1}]	***0***	***19,5***	***26,4***	***30,3***	***33***	***35,1***	***36,7***	***38,1***	***39,2***	***40,2***	***41***
Temp. [°C]	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**
α [W.m^{-2}.K^{-1}]	***41,7***	***42,4***	***43***	***43,5***	***44***	***44,4***	***44,8***	***45,1***	***45,5***	***45,8***	***46***
Temp. [°C]	**1100**	**1150**	**1200**	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**	**1550**	**1600**
α [W.m^{-2}.K^{-1}]	***46,3***	***46,5***	***46,8***	***47***	***47,2***	***47,4***	***47,5***	***47,7***	***47,9***	***48***	***48,1***
Temp. [°C]	**1650**	**1700**	**1750**	**1800**	**1850**	**1900**	**1950**	**2000**	**2050**	**2100**	**2150**
α [W.m^{-2}.K^{-1}]	***48,3***	***48,4***	***48,5***	***48,6***	***48,8***	***48,9***	***49***	***49,1***	***49,2***	***49,2***	***49,3***

2.2 Heat transfer by radiation

Radiation is a special way of heat sharing. It differs from the other ways because it does not need a mediating substance. The radiant energy depends only on the temperature shape and transit by an electromagnetic wave with a different wavelength. Radiation heat sharing computation is derived from the Stefan-Boltzmann law.

In Tab. 2 the radiation heat transfer coefficient values for different temperatures of the radiation shape are shown.

Tab. 2 Heat transfer by radiation

Temp. [°C]	**20**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
α [W.m^{-2}.K^{-1}]	***0***	***6,7***	***8,5***	***10,8***	***13,5***	***16,6***	***20,4***	***24,6***	***29,5***	***35,1***	***41,3***
Temp. [°C]	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**
α [W.m^{-2}.K^{-1}]	***48,3***	***56,1***	***64,7***	***74,2***	***84,5***	***95,9***	***108,2***	***121,6***	***136***	***151,6***	***168,3***
Temp. [°C]	**1100**	**1150**	**1200**	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**	**1550**	**1600**
α [W.m^{-2}.K^{-1}]	***186,3***	***205,5***	***226***	***247,8***	***271***	***295,6***	***321,7***	***349,3***	***378,5***	***409,2***	***441,6***
Temp. [°C]	**1650**	**1700**	**1750**	**1800**	**1850**	**1900**	**1950**	**2000**	**2050**	**2100**	**2150**
α [W.m^{-2}.K^{-1}]	***475,6***	***511,4***	***548,9***	***588,2***	***629,4***	***672,5***	***717,5***	***764,4***	***813,4***	***864,5***	***917,6***

2.3 Temperature dependence of heat transfer coefficient to the surroundings

The whole heat transfer coefficient is derived by a sum of individual factors (heat transfer coefficient by convection and heat transfer coefficient by radiation). To the temperature of 593°C the heat transfer by convection is higher and from this temperature we can observe a steep increase of radiation. In Tab. 3 there are values of the whole heat transfer coefficient for the different surface temperatures.

Tab.3 Heat transfer coefficient to the surroundings

Temp. [°C]	**20**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
α [W.m^{-2}.K^{-1}]	***0***	***26,2***	***34,9***	***41,1***	***46,5***	***51,7***	***57,1***	***62,7***	***68,7***	***75,3***	***82,3***
Temp. [°C]	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**
α [W.m^{-2}.K^{-1}]	***90,1***	***98,5***	***107,7***	***117,7***	***128,5***	***140,3***	***153***	***166,7***	***181,5***	***197,3***	***214,4***
Temp. [°C]	**1100**	**1150**	**1200**	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**	**1550**	**1600**
α [W.m^{-2}.K^{-1}]	***232,6***	***252***	***272,7***	***294,8***	***318,2***	***343***	***369,2***	***397***	***426,3***	***457,2***	***489,7***
Temp. [°C]	**1650**	**1700**	**1750**	**1800**	**1850**	**1900**	**1950**	**2000**	**2050**	**2100**	**2150**
α [W.m^{-2}.K^{-1}]	***523,9***	***559,8***	***597,4***	***636,9***	***678,2***	***721,3***	***766,4***	***813,5***	***862,6***	***913,7***	***966,9***

3 Experimental measurement of heat transfer coefficient to the environment

Another possibility is to find the heat transfer coefficient by experimental measurement. Preparing the Experiment, however, requires very precise accuracy. Firstly is it important to find the right amount of heat transmitted to the material and subsequently with the help of the temperature registrations of surface thermocouples and empiric relations, to retroactively find the heat transfer coefficient. The second possibility is to measure only the thermal cycles with the help of the surface thermocouples on the tested plate and the subsequent determination of the heat transfer with the indirect method of numerical analyses.

The biggest problem with the experimental test is the high temperature. We can say, that by experimental measurement we can find the required values of the heat transfer coefficient at the temperature of 650°C. With temperatures higher than 700°C the whole measurement is charged by a number of mistakes, starting with the compensation line and finishing with the radiation of thermocouples. In Tab 4 there are heat transfer coefficient values acquired on the basis of the indirect experimental method.

Tab. 4 Experimental measurement of heat transfer coefficient to the environment

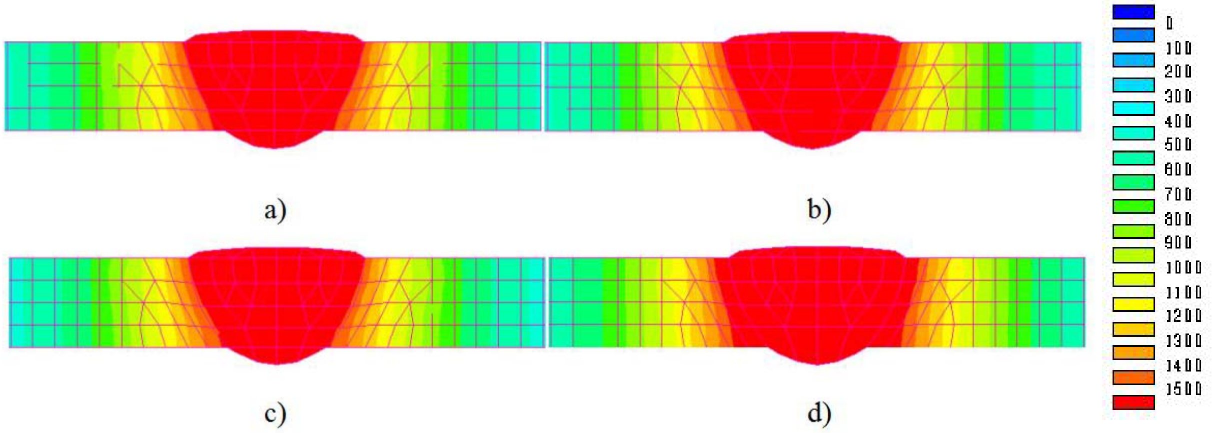
Temp. [°C]	**20**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
α [W.m^{-2}.K^{-1}]	***19***	***19,5***	***20***	***22,3***	***25***	***28,7***	***32***	***36***	***40***	***44,2***	***49***
Temp. [°C]	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**
α [W.m^{-2}.K^{-1}]	***54,5***	***60***	***67,9***	***75,8***	***83,7 ****	***92 ****	***101 ****	***111 ****	***124 ****	***140 ****	***159 ****
Temp. [°C]	**1100**	**1150**	**1200**	**1250**	**1300**	**1350**	**1400**	**1450**	**1500**	**1550**	**1600**
α [W.m^{-2}.K^{-1}]	***181 ****	***206 ****	***234 ****	***265 ****	***293 ****	***325 ****	***362 ****	***410 ****	***461 ****	***528 ****	***610 ****

* simulations based on verified estimations

4 Comparing the influence of heat transfer coefficient to the simulation accuracy

Four basic simulations were carried out to compare the influence of the different heat transfer coefficients to the surroundings:

1. Simulations with the heat transfer coefficient to the surroundings obtained on the basis of indirect experimental method base (tab. 4).
2. Simulations with the heat transfer coefficient to the surroundings obtained on the basis of theoretical computation (computed with convection and radiation (tab.3.).
3. Simulations with the heat transfer coefficient to the surroundings obtained on the basis of theoretical computation, when only heat transfer by convection is considered (tab. 1.).
4. Simulations with the heat transfer coefficient to the surroundings obtained on the basis of theoretical computation, when only heat transfer by radiation is considered (tab. 2.).



a) b)

c) d)

Fig. 1.a,b,c,d Melting zone size on the basis of different heat transfer coefficients

The simulation with the heat transfer coefficient to the surroundings was chosen as a comparable simulation obtained on the basis of the indirect experimental method. For this simulation it was proved that the heat source as well as the melting area conforms to the weld pool shape model. In this manner the conformed source was used for all simulations with the different heat transfer coefficients to the surroundings. In the picture (1. a, b, c, d) it is seen, how different heat transfer coefficients to the surroundings influenced the melting zone size. In picture 1.a the heat transfer coefficient is obtained by the experiments. In picture 1.b the heat transfer coefficient is obtained by the theoretical computation, figure 1.c is for the heat transfer coefficient to the surroundings by radiation and figure 1.d is for the heat transfer coefficient to the surroundings by convection.

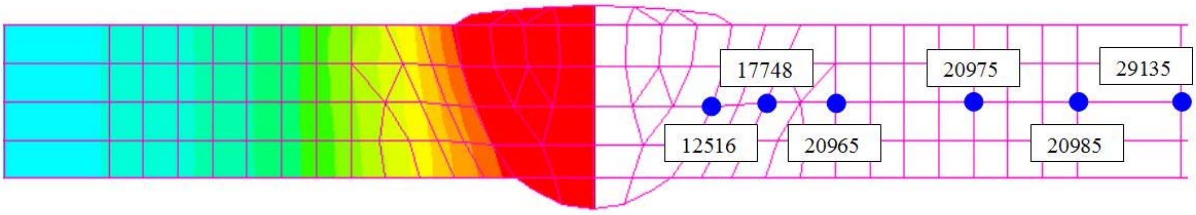


Fig. 2 Node points in which deviations of temperature field were investigated

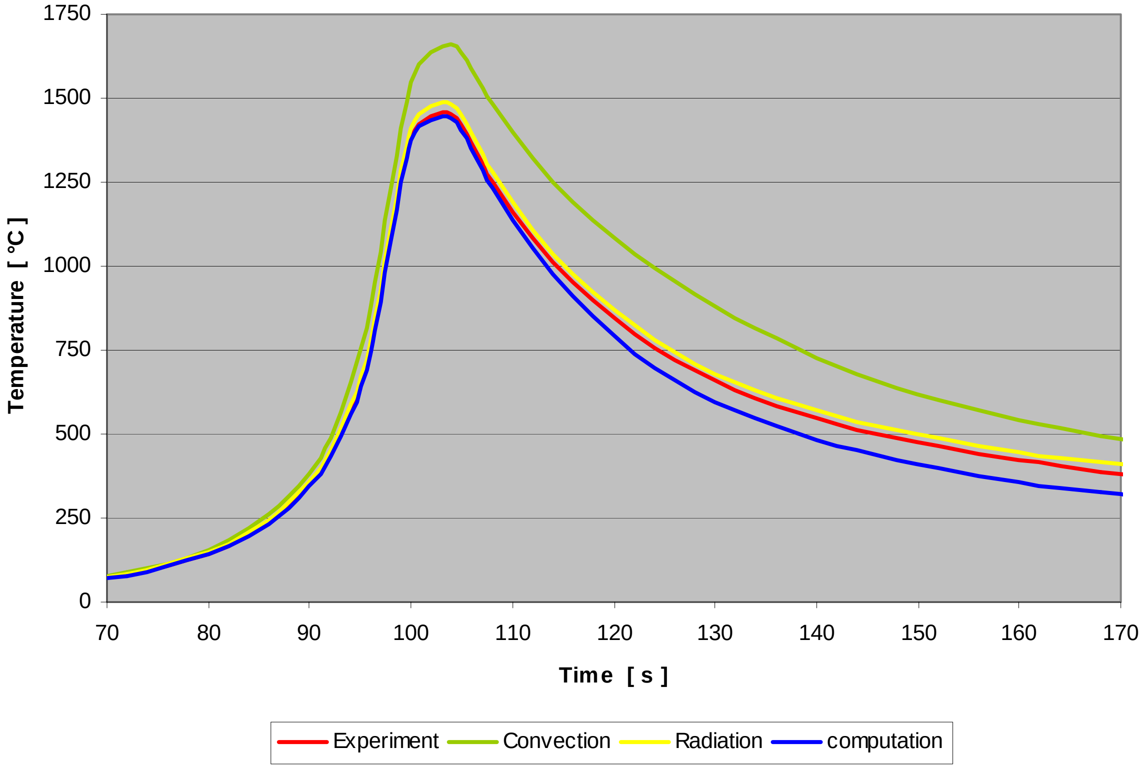


Fig. 3 Time dependence of temperature for different heat transfer in node point 12516

Further, from the shape model five node points (fig. 2) were chosen, in which the deviation from the temperature field was investigated. Node point 12516 is on the boundary between the melting zone and the heat affected zone, node point 17748 is situated in the heat affected zone about 2 mm from the melting boundary. Node point 20965 is situated at a distance of 4,2mm, node point 20975 at a distance of 8,2 mm, node point 20985 at a distance of 12,2 mm and node point 29135 at a distance of 15,2 mm from the melting boundary. In the figure 4 the temperature-time dependence for the different heat transfer values in node point 12516 is shown. From the graph it is seen that the maximum deviations up to the welding time of 104 s when point 12516 passed the heat source (fig. 2), were not higher than 14,6 % for the heat transfer by convection. Up to this time the maximum temperature deviation was 212,8 °C. But for the heat transfer by radiation and the computed heat transfer with convection and radiation the maximum deviations were only 2,2 %. Not until during the cooling process of point 12516 did a higher percentage of temperature deviations begin to appear. Had we expected cooling in the temperature interval of 800 – 500 °C, which is important from the standpoint of the resulting welding structure, then the maximal deviation for the heat transfer by radiation would have been 4,6% and for the heat transfer by radiation and convection 12,2 %.

When the distance from the melting boundary increases, the percentage of deviations in the temperature fields slightly decreases. E.g. for the distance 15,2 mm the heat transfer by radiation is only 3,9 % and for the heat transfer by radiation and convection the maximal deviation decreases to 9,1 %. This information is important for imagining the temperature fields' location in space and time.

5 Conclusion

As we have seen from the temperature curve dependence (fig. 3), the influence of the individual partial heat transfer coefficient to the surroundings becomes evident only after achieving the maximum temperature. Using the heat transfer to the surroundings by means of the simulation computations of the non-stationary temperature fields is not appropriate.

As it was noted in the previous section, to get the temperature dependence of the heat transfer coefficient to the surroundings by means of the experimental test is strongly dependant on accuracy. By using the indirect method we can get as good a result of the thermal fields as by using the computed heat transfer coefficient, problems however can arise by using the different heat source types. For example with the sources which have high power density in the incidence area. That is why we recommended by means of welding simulations using the heat transfer coefficient to the surroundings from the computations (radiation).

The maximal percentage of deviation between the simulations with heat transfer from the experiments and the simulations with the computed heat transfer is 7,2% with temperatures lower than 350°C. The maximal deviation is however with these temperatures only 27,6°C which is a satisfactory result.

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Ing. Jaromír Moravec, Ph.D.

VLIV A VOLBA SOUČINITELE PŘESTUPU TEPLA DO OKOLÍ PŘI SIMULACÍCH TEPLOTNÍCH POLÍ V PROGRAMU SYSWELD

Svařování je specifický děj, probíhající ve velmi krátkém časovém intervalu, s malou natavenou oblastí a s nelineárními závislostmi. Proto je popis tohoto děje velmi obtížný. Při výpočtech teplotních polí vycházíme z teplotně-fyzikálních dat daných Fourierovu diferenciální rovnici a z teplotní závislosti součinitele přestupu tepla do okolí. Právě na součiniteli přestupu tepla do okolí je možné ukázat, jak složité je získat kvalitní vstupní data pro simulační výpočet. Součinitel přestupu tepla se mění podle toho, zda se jedná o rovinu vertikální, horizontální, nebo rovinu skloněnou pod nějakým úhlem. Závisí také na tom, zda se jedná o horní povrch desky, nebo o spodní povrch desky, protože rozdíl zde může činit až 30%. Na simulacích v programu Sysweld bude ukázáno, jak různé druhy součinitele přestupu tepla do okolí mohou ovlivnit celkový výsledek simulačního výpočtu.

EINFLUSS UND WAHL DER WÄRMEÜBERGANGSKOEFFIZIENTEN BEI DER SIMULATION DER TEMPERATURFELDER IM SYSWELD-PROGRAMM

Schweißen ist ein besonderer Prozess, der in einem sehr kurzen Zeitintervall verläuft und in einem kleinen Rauminhalt des Schweißbades mit nichtlinearen Abhängigkeiten erfolgt. Daher ist die Beschreibung dessen Prozesses sehr schwierig. Bei der Berechnung von Temperaturfeldern muss man von den thermo-physikalischen Daten in der Fourier-Differentialgleichung und der Temperaturabhängigkeit des Wärmeübergangskoeffizienten ausgehen. Gerade auf dem Wert von den Wärmeübergangskoeffizienten ist es möglich zu zeigen, wie schwierig es ist, die hochwertigen Eingabedaten für Simulationsrechnung zu bekommen. Wärmeübergangskoeffizienten ändern sich je nachdem, ob die Fläche vertikal, horizontal oder in einem beliebigen Winkel steht. Es hängt auch davon ab, ob es sich um die Oberseite oder Unterseite der Platte handelt. Der Unterschied kann um bis zu 30% steigen. Mit dem Simulationsprogramm SYSWELD wird gezeigt, wie die verschiedenen Werte der Wärmeübergangskoeffizienten das Gesamtergebnis der Simulationsrechnung beeinflussen können.

WYBÓR ORAZ WPŁYW WSPÓŁCZYNNIKA WYMIANY CIEPŁA NA POLE TEMPERATUR W SYMULACJACH NUMERYCZNYCH PROCESÓW SPAWANIA

Spawanie jest procesem specjalistycznym, który przebiega w bardzo krótkim czasie z małymi strefami nadtopienia oraz nieliniowymi zależnościami pomiędzy parametrami zjawiska. Opis takiego procesu jest skomplikowany i nie trywialny. Obliczenia pola temperatur opierają się na termo-fizycznych danych uzyskanych z równania różniczkowego Fouriera oraz na zależnościach temperaturowych współczynnika wymiany ciepła z otoczeniem. Współczynnik wymiany ciepła stanowi przykład pokazujący trudności w osiągnięciu dobrej jakości danych wejściowych niezbędnych do wykonania analizy numerycznej. Jego zmiany zależą od typu płaszczyzny: wertykalnej, horyzontalnej oraz od kątów, pod którymi skierowane jest narzędzie spawalnicze. Znaczenie ma również rozpatrywana płaszczyzna części spawanej: górna lub dolna, ponieważ różnica w wartości współczynnika wymiany ciepła może sięgać do 30%. Symulacje wykonane z wykorzystaniem oprogramowania SYSWELD pokazują jak współczynnik wymiany ciepła z otoczeniem może wpłynąć na wyniki analizy numerycznej.