NUMERICAL MODELLING OF THERMAL CYCLES IN STEEL DURING SURFACING AND WELDING WITHOUT PREHEATING AND THEIR COMPARISON WITH EXPERIMENTAL DATA

By means of the ANSYS 5.6 programme thermal fields in the heat affected zone (HAZ) regions of overlay-welded and welded steel without preheating have been modelled and multiple thermal cycles numerically calculated. The designed geometric models are of the two-dimensional type with 3-D characteristics. The number of overlay-welded and welded layers was varied from 1 to 6. After numerical calculations for the individual overlay-welded and welded layers, the course of thermal cycles was analyzed for the 1st, 3rd and 6th layer. Such a procedure followed from practical utilization of the computation results. ASME regulations recommend welding of minimum 6 layers to get the desired tempering effect of hardened microstructures in the HAZ, which are characterized by unfavourable toughness. Parameters of thermal cycles in the HAZ’s of overlay-welded and welded steel, calculated numerically and measured experimentally, were compared. Moreover the effect of temperature field asymmetry was raised, which is caused by the heat flow from successive layers of the overlay weld.

Key words: thermal welding cycle, Heat Affected Zone, cooling time, numerical modelling

1. INTRODUCTION

The post-weld heat treatment (PWHT) is an important problem, as is the case at welding of components in the power industry. The objective of PWHT is the maximum reduction of welding residual stresses and the improvement of heat affected zone (HAZ) and weld metal toughness. However, in the case of repair welding of big objects PWHT may cause serious difficulties. In those situations an effective means of ensuring proper high HAZ toughness is the application of so-called “temper bead welding”. The method consists in such a means and sequence of laying individual weld beads, to temper the martensitic microstructure in the HAZ of previously welded beads, by the controlled
welding thermal cycle. The temper bead welding technique enables lowering of hardness of martensitic and upper bainitic microstructures, which occur in the coarse grain region of the HAZ, and in consequence, toughness improvement of these welded joint regions.

To replace effectively the traditional PWHT by the temper bead welding technique it is essential to gain knowledge on the temperature distribution at individual weld beads (layers) and on the influence of welding thermal cycles on structural transformations in the coarse grain HAZ regions.

2. MATHEMATICAL MODELLING OF TEMPERATURE FIELDS AT VARIOUS HAZ REGIONS BY MEANS OF THE ANSYS PROGRAM

Results of numerical computations, performed by the application of the ANSYS program with a partition ability of the identified area into 32 thousand nodes and elements, are presented in this paper. Modelling of thermal fields in the HAZ region of steel has been performed under the influence of multiple welding thermal cycles with different parameters (maximum temperatures $T_{\text{max}}$ and $t_{8/5}$ cooling times). The designed two-dimensional models with three-dimensional attributes have mapped multilayer welding and surfacing without preheating. The number of weld layers has been changed from 1 to 6. The technological input data (welding method, welding current $I$ [A], arc voltage $U$ [V], welding speed [cm/s], time passed between welding of successive layers, initial and interpass temperature [$^\circ$C] and the joint thickness [mm]) have been taken from the results of research projects [8] and [9]. The physical properties of modeled steels, such as: mass density $\text{DENS}$ ($\gamma$) [kg/mm$^3$], thermal conductivity $KXX$ ($\lambda$) [cal/mm·s·$^\circ$C] and specific heat $c$ [cal/kg·$^\circ$C] were taken from the literature ($\text{DENS}$, $KXX$ – designations used in the ANSYS program) [2, 4, 6].

Thermal cycles measured during TIG overlay-welding under argon shielding are presented in the research report [1]. The course of the experiment was as follows. On the SM400A steel plate six layers have been successively overlay-welded, one after another. The first layer consisted of six runs, and every next layer of one run less. The scheme of the overlay process is shown in Fig. 1.

Fig. 1. Scheme of the overlay welding [8]
Rys. 1. Schemat sposobu układania napoiny [8]
For numerical calculations a geometrical model has been used, which is shown in Fig. 2 and 3. The model has represented the experimental conditions.

The following input data were used for numerical computations:

a) **General data:**
- base material: unalloyed steel,
- welding filler metal: alloyed,
- overlay-welding method: TIG without preheating, six layers,
- plate thickness: \( t = 20 \text{ mm} \).

b) **Technological data:** – Table 1.

<table>
<thead>
<tr>
<th>Welding heat input ( Q \text{ [kJ/cm]} )</th>
<th>Welding current ( I \text{ [A]} )</th>
<th>Arc voltage ( U \text{ [V]} )</th>
<th>Welding speed ( v \text{ [cm/min]} )</th>
<th>Initial temperature ( ^\circ\text{C} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,5</td>
<td>100</td>
<td>9,2</td>
<td>15 ( 1) )</td>
<td>20</td>
</tr>
<tr>
<td>9,4</td>
<td>150</td>
<td>10,5</td>
<td>15 ( 1) )</td>
<td>20</td>
</tr>
<tr>
<td>14,8</td>
<td>200</td>
<td>12,3</td>
<td>15 ( 1) )</td>
<td>20</td>
</tr>
</tbody>
</table>

\( 1) \) average value of welding speed.

c) **Physical properties:** – Tables 2 and 3.
**Table 2**

Room temperature data (20 °C) [2, 5, 6]

<table>
<thead>
<tr>
<th>Physical value</th>
<th>Material 1 base material (unalloyed steel)</th>
<th>Material 2 melted weld metal (alloyed steel)</th>
<th>Material 3 solidified weld metal (alloyed steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density DENS *) [kg/mm³]</td>
<td>0,79 × 10⁻⁵</td>
<td>0,70 × 10⁻⁵</td>
<td>0,70 × 10⁻⁵</td>
</tr>
<tr>
<td>Thermal conductivity KXX *) (λ) [cal/(mm·s·°C)]</td>
<td>0,96 × 10⁻²</td>
<td>0,2 × 10⁻³</td>
<td>0,4 × 10⁻²</td>
</tr>
<tr>
<td>Specific heat c [cal/(kg·°C)]</td>
<td>174</td>
<td>160</td>
<td>160</td>
</tr>
</tbody>
</table>

Where: *) designations used in the ANSYS program.

**Table 3**

Thermal conductivity at various temperatures for the base material and weld metal [2, 5, 6]

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Thermal conductivity KXX (λ) [cal/(mm·s·°C)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base material 1</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>0,0096</td>
</tr>
</tbody>
</table>

Numerical computations have been performed for the six overlay welded layers 1 to 6, based on the model presented in Fig. 3. A general view of the models and calculated thermal fields for the individual weld layers contains Table 4.

**3. NUMERICAL MODELLING RESULTS FOR OVERLAY WELDING**

After numerical computations have been performed for the individual overlay-welded layers, the course of thermal cycles has been analysed for the first, third and sixth layer. The reason was the necessity of practical utilization of the calculated results. The ASME regulations [1] recommend a minimum of six welded (overlay-welded) layers to get the desired tempering effect of hardened microstructures, which occur in the HAZ and are characterized by unfavourable toughness.

Results of numerical calculations for the overlay-welded layer No. 1 are presented in Fig. 4 ÷ 6, for the layer No. 3 – in Fig. 7 and 8, and for the layer No. 6 – in Fig. 9 and 10.
### Table 4

General view of the models and calculated thermal fields for the individual weld layers [10]

Widok ogólny modeli i obliczonych numerycznie pól temperatury dla kolejnych napawanych warstw [10]

<table>
<thead>
<tr>
<th>No of overlay weld layer</th>
<th>General view of the model</th>
<th>Numerically calculated thermal field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>6</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Fig. 4. Welded layer No. 1. Temperature distribution in nodes and fragment of temperature field
Rys. 4. Warstwa napawana nr 1. Rozkład temperatur w węzłach i fragment pola temperatur

Fig. 5. Welded layer No. 1. Thermal cycles in nodes from Fig. 4 with $T_{\text{max}} = 1310, 1190$ and $1095 \degree C$
Rys. 5. Warstwa napawana nr 1. Widok ogólny cykli cieplnych wybranych w węzłach o temperaturach maksymalnych $T_{\text{max}} = 1310, 1190$ i $1095 \degree C$ z rys. 4

Fig. 6. Welded layer No. 1. Example of determination of cooling time between 800 and 500 $\degree C$ ($t_{8/5}$) for thermal cycles from Fig. 5
Rys. 6. Warstwa napawana nr 1. Przykład wyznaczenia czasów stygnięcia w zakresie temperatur pomiędzy 800 a 500 $\degree C$ ($t_{8/5}$) dla cykli cieplnych z rys. 5

Fig. 7. Welded layer No. 3. Thermal cycles in nodes with $T_{\text{max}} = 875, 804$ and $740 \degree C$
Rys. 7. Warstwa napawana nr 3. Widok ogólny cykli cieplnych wybranych w węzłach o $T_{\text{max}} = 875, 804$ i $740 \degree C$

Fig. 8. Welded layer No. 3. Determination of $t_{8/5}$ cooling time for thermal cycles from Fig. 7
Rys. 8. Warstwa napawana nr 3. Wyznaczenie czasów stygnięcia $t_{8/5}$ dla cykli cieplnych z rys. 7

Fig. 9. Welded layer No. 6. Heat flux propagation [11] after welding termination
4. DEVELOPMENT OF THE GEOMETRIC MODEL CONCEPT AND GENERATION OF THE COMPUTATION MESH FOR WELDING PROCESS MODELLING

One of the most important stages of the modelling process was the adoption of an optimal, from the practical point of view, geometrical model of the welded joint. The final shape of the geometrical model was decided by the welding practice and repair regulations of welded joints by means of the temper bead technique. The following course of reasoning was approved. In a hypothetical structural part under service (e.g. a power plant structure) a crack has been detected, which causes a risk for the further safe operation. The defect has to be repaired by welding (Fig. 11).

For numerical calculations the geometric model shown in Fig. 12 and 13 was applied.
5. MODELLING OF THERMAL FIELDS IN THE HAZ AT WELDING CONDITIONS

The following input data have been taken for numerical calculations.

a) General data:
   - base material (1): unalloyed steel,
   - filler metal (3): alloyed steel,
   - welding method: TIG, without preheating, six layers in the weld,
   - plate thickness: $t = 40$ mm.

b) Technological data: welding parameters as in Table 1.

c) Physical properties: room- and elevated temperature data as given in Tables 2 and 3.

6. NUMERICAL MODELLING RESULTS FOR WELDING

Results of numerical calculations for the welded layer No. 1 are presented in Fig. 14 ÷ 16, for the layer No. 3 – in Fig. 17 and 18, and for the layer No. 6 – in Fig. 19 ÷ 22.
Fig. 14. Welded layer No 1. Temperature distribution in nodes and temperature field
Fig. 15. Welded layer No 1. Thermal cycle in a node at a distance of 2.8 mm from the welding groove bottom with a temperature of 1318 °C

Rys. 14. Warstwa spawana nr 1. Rozkład temperatur w węzłach wraz z polem temperatur
Rys. 15. Warstwa spawana nr 1. Widok ogólny cyklu cieplnego wybranego w węźle w odległości 2.8 mm od dna rowka spawalniczego o temperaturze maksymalnej 1318 °C

Fig. 16. Welded layer No 1. Determination of \( t_{8/5} \) cooling time for the thermal cycle in Fig. 15
Fig. 17. Welded layer No 3. The weld penetration depth into the base material determined by the 1500 °C isotherm

Rys. 16. Warstwa spawana nr 1. Wyznaczenie czasu stygnięcia \( t_{8/5} \) dla cyklu cieplnego z rys. 15
Rys. 17. Warstwa spawana nr 3. Zasada sprawdzania głębokości wtopienia spoiny w materiał podstawowy w oparciu o izotermę 1500 °C

Fig. 18. Welded layer No 3. Heat flux propagation 30 s after welding termination
Fig. 19. Welded layer No 6. Temperature distribution in nodes

Rys. 18. Warstwa spawana nr 3. Strumień rozchodzenia się ciepła po zakończeniu spawania (po czasie 30 s)
Rys. 19. Warstwa spawana nr 6. Rozkład temperatur w węzłach
7. DISCUSSION OF RESULTS

In Table 5 thermal cycle parameters (maximum temperature $T_{\text{max}}$ and $t_{0.5}$ cooling time) in the HAZ region, obtained by numerical calculations for overlay welding and welding, are compared with those determined experimentally.

The data obtained by numerical modelling and presented in Table 5, enable anticipation of thermal processes development in welded joints. From data in Table 5 it is evident, that beginning from the 4th layer up to the 6th layer, in the HAZ under the weld the maximum temperatures of the thermal cycles are lower than 800 °C, and the analysis of the increasing cooling time is not justified from the point of view of metal science.
Comparison of overlay welding and welding thermal cycle parameters for the HAZ region obtained by numerical calculations and determined experimentally [10]

Porównanie parametrów cyklu cieplnego napawania i spawania w obszarach SWC uzyskanych numerycznie i eksperymentalnie przy napawaniu / spawaniu [10]

<table>
<thead>
<tr>
<th>Layer No in the overlay weld / weld</th>
<th>Welding thermal cycle parameters determined:</th>
<th>experimentally for overlay welding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>numerically</td>
<td>for overlay welding</td>
</tr>
<tr>
<td></td>
<td>overlay welding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>welding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{\text{max}}$ [$^\circ$C]</td>
<td>$t_{\text{8/5/CT}}$ [s]</td>
</tr>
<tr>
<td>1</td>
<td>1310</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>1052</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>875</td>
<td>39</td>
</tr>
<tr>
<td>4</td>
<td>685</td>
<td>61</td>
</tr>
<tr>
<td>5</td>
<td>522</td>
<td>117</td>
</tr>
<tr>
<td>6</td>
<td>440</td>
<td>-</td>
</tr>
</tbody>
</table>

Where: $d$ – distance from the weld groove bottom into the HAZ,

$d_1$ – distance from the thermocouple tip to the fusion line,

CT – cooling time for thermal cycles with the maximum temperature $T_{\text{max}}$ lower than 800 $^\circ$C, determined for the $T_{\text{max}}$ – 500 $^\circ$C temperature range,

$^1$) – maximum temperature value of the thermal cycle after taking into consideration the thermal inertia.

In real welding conditions the thermal field shows asymmetry, which is caused by heat transfer during welding of consecutive beads in the layer. An attempt was made in numerical calculations to find, how does the thermal field asymmetry influence the thermal conditions, which accompany the heating and cooling process of an overlay-welded specimen. An example of thermal field asymmetry in an overlay-welded layer is shown in Fig. 23 and 24.
Figure 23 shows, that just after finishing the overlay-welding of six beads in the first layer a differentiation of temperatures occurs, the highest temperature is recorded in the last bead (on the right), and the lowest – in the first one (on the left in Fig. 23). After 120 seconds of the cooling process the temperatures level out in the hot specimen, and the asymmetry in the temperature field distribution decays (see Fig. 24). It results, that the analysis of thermal processes in the central part of the overlay-welded specimen can be done without taking into consideration the influence of the temperature field asymmetry (the reading of temperature values and thermal cycles is done along the vertical symmetry axis of the overlay-welded specimen).

Beginning with the layer No 4, the effect of thermal inertia was observed. For example, at the thermal cycle selected in a node with a maximum temperature of 649 °C (Fig. 25), the temperature still rises and reaches the maximum value of 815 °C. The effect of thermal inertia can be explained by changes of the thermal conductivity KXX (λ) with temperature, as shown in Fig. 26.
It follows from Fig. 26a, that for materials characterized by great thermal conductivity values ($\lambda >> 1$) the effect of thermal inertia does not occur. But the effect can be observed for materials with thermal conductivity values $\lambda$ much lower than 1 at 20 °C (Fig. 26b) and its further decrease with increasing temperature [7].

From comparison of numerically calculated overlay welding data with those determined experimentally for the individual layers (Table 5) it is apparent, that the thermal cycle parameters (maximum temperature $T_{\text{max}}$ and $t_{8/5}$ / CT cooling times) show nearly similar values.

From the results of numerical calculations performed for the welding process it can be seen, that the cooling time increases for the consecutive welded layers.

### 8. CONCLUSIONS

1. The upper part of the HAZ cooling curve is characterized by the highest heat abstraction, that is, the greatest temperature gradient, which slows down with time (Fig. 15) and has an effect on the temporary conditions of allotropic structural transformations and precipitations which occur at high, medium and lower temperatures.

2. When welding a low carbon steel, the available austenite ($\gamma \rightarrow \alpha$) transformation time is shorter than that available for the bainite transformation, which occurs at lower temperatures. That is why the fraction of hardening microstructures, especially bainite, can increase, which may deteriorate the HAZ toughness.
3. By numerical modelling, values of thermal cycle parameters (maximum temperatures and cooling times) comparable with the experimental ones have been obtained. It can be concluded therefore, that on the basis of numerical modelling results, the development and course of thermal processes in real welded joints can be anticipated.

REFERENCES


Praca wpłynęła do Redakcji dd.mm.2006 Recenzent: prof. dr hab. inż. Edmund Tasak

MODELOWANIE NUMERYCZNE CYKLI CIEPLNYCH W STALI PODCZAS NAPAWANIA I SPAWANIA BEZ PODGRZEWANIA WSTĘPNEGO W ODNIESIENIU DO DANYCH EKSPERYMENTALNYCH

Streszczenie

Przedstawiono proces modelowania i wyniki obliczeń numerycznych przy użyciu programu ANSYS 5.6. Przeprowadzono modelowanie pól temperatur w obszarach strefy wpływu ciepła (SWC) stali w warunkach oddziaływania wielokrotnych cykli cieplnych cykli cieplnych spawania o różnych parametrach. Badane modele matematyczne odwzorowywały proces napawania i spawania wielowarstwowego w wariancie bez podgrzewania wstępnego. Utworzono modele
geometryczne są modelami płaskimi o cechach przestrzenności. Liczba napawanych i spawanych warstw zmieniała się od 1 do 6. Po przeprowadzeniu obliczeń numerycznych dla poszczególnych napawanych i spawanych warstw analizowano przebiegi cykli cieplnych dla pierwszej, trzeciej i szóstej warstwy napoiny lub spoiny. Taki sposób postępowania wynikał głównie z praktycznego wykorzystania wyników obliczeń. Przepisy ASME zalecają wykonanie minimum sześciu warstw spawanych lub napawanych w celu uzyskania pożądanego efektu odpuszczania struktur hartowniczych, które występują w obszarze SWC i charakteryzują się niekorzystnymi własnościami plastycznymi. W rozdziale dotyczącym analizy wyników badań m.in. dokonano porównania parametrów cyklu cieplnego napawania i spawania w obszarach SWC stali, które uzyskano numerycznie z analogicznymi parametrami uzyskanymi eksperymentalnie. Ponadto poruszono zagadnienie zjawiska niesymetryczności temperatury, które występuje w wyniku nagrzewania podczas układania kolejnych ścięg napoiny.

Słowa kluczowe: cykl cieplny spawania, strefa wpływu ciepła, czas chłodzenia, modelowanie numeryczne