EXPERIMENTAL AND ANALYTICAL EVALUATION OF PREHEATING TEMPERATURE DURING MULTIPASS REPAIR WELDING

by

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Experimental measurement and analytical calculation of preheating, i. e. interpass temperature during multi-pass repair welding has been presented. Analytical calculation is based on heat transfer analysis, whereas measurements have been performed by thermovision camera. Repair welding was performed on crane wheels in the Steelworks Smederevo. Comparison of results indicated that analytical calculation is good enough as the first approximation, but it needs further elaboration, e. g. taking into account the radiation component of heat dissipation and/or temperature dependence of material thermomechanical properties.

Key words: *preheating temperature, repair welding, heat transfer, thermovision camera*

Introduction

Preheating is used as the common method to reduce cooling rate during welding, which is beneficial from different points of view (weldment microstructure, *i. e.* better properties and lower sensitivity to cracking, lower residual stresses) [1]. Therefore, it is of utmost importance to determine preheating temperature during multi-pass welding, like repair submerged arc welding (SAW), as precisely as possible. Toward this aim, analytical calculation, based on heat transfer analysis, is commonly used engineering tool, but it needs some simplifications in order to be practical, making its accuracy somewhat questionable. This problem is analyzed and described in numerous references, using simple heat transfer analysis, which inevitably neglect effects such as radiation and temperature dependence of material thermomechanical properties, *e. g.* [2, 3]. On the other hand side, numerical methods, typically based on the finite element method, provide more precise solutions for thermomechanical problems such as welding, since they can take into account radiation effects, and change of material thermomechanical properties with change of temperature, but they are far more complicated to use [4-6]. Therefore, from an engineer point of view, analytical calculation of preheating temperature is still important method, but it needs experimental verification to check it accuracy and applicability. Experimental measurement is nowadays available in its simplest ever form, namely infrared measurements, performed by thermovision camera [6, 7].

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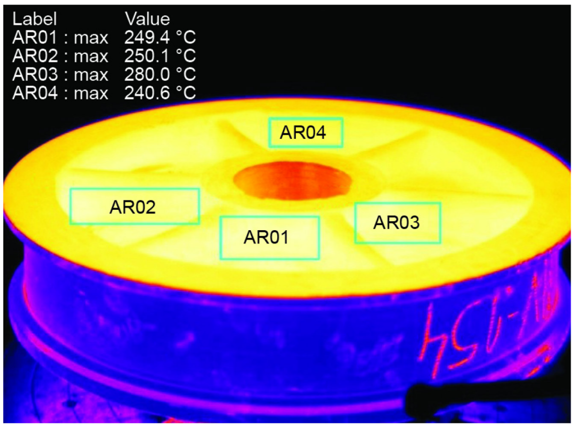


Figure 1. Thermovision indication of crane wheel after preheating (*for color image see journal web site*)

Table 1. The SAW parameters

Pass no.	Filler metal	Arc current, I, [A]	Arc voltage, U, [V]	Welding speed, v, [cmmin^{-1}]
1	WLDC-9	300	28	50

In this paper simple analytical calculation, based on heat transfer analysis, is applied to determine temperature during cooling phase of repair welding of crane wheels in the Steelworks Smederevo, and results compared with those obtained by using thermovision camera, *i. e.* infrared measurements.

Basic data about repair welding

Crane wheels, Ø630, made of cast steel GS-42CrMo4, frequently undergo repair welding. Prescribed temperature, as defined by filler metal producer, is 250 °C [8]. It is very important to control this temperature, so that cooling rate can be controlled, as well. As an illustration, fig. 1 shows crane wheel, as recorded by thermovision camera, immediately after being taken out of preheating furnace. The SAW for repair welding of crane wheels, with parameters, are given in tab. 1.

Analytical calculation

Heat input per unit length for an electric arc welding is defined by:

$$E = \frac{60IU}{1000v}\eta \tag{1}$$

where η is the welding efficiency coefficient, for SAW, typically 0.8-0.95.

Taking values for arc current, arc voltage, and welding speed, from tab. 1, one can calculate $E = 9.072$ kJ/cm. Now, one can calculate total heat input for one pass:

$$Q_u = El \tag{2}$$

where l is the length of welding, which can be calculated as (n is the number of runs in one pass): $l = n\,2R\pi = 8\cdot 2\cdot 30\pi$, $l = 1508$ cm, and $Q_u = 13681$ kJ.

Heat dissipation during welding of crane wheel is equal to the heat convection into surrounding ambient air, if radiation is neglected:

$$|\mathrm{d}Q| = \alpha A(t - t_0)\mathrm{d}\tau = -V\rho c\mathrm{d}t \tag{3}$$

Therefore:

$$\int_{t_p}^{t} \frac{\mathrm{d}t}{t - t_0} = -\frac{\alpha A}{V\rho c}\int_0^{\tau} \mathrm{d}\tau \tag{4}$$

By integrating eq. (4), one can get:

$$\ln\frac{t-t_0}{t_p-t_0}=-\frac{\alpha A\tau}{V\rho c}\qquad i.\,e.\qquad \frac{t-t_0}{t_p-t_0}=\mathrm{e}^{-\frac{\alpha A\tau}{V\rho c}} \tag{5}$$

where t is the temperature, t_0 = 18 °C – the ambient air, taken as constant, t_p = 250 °C – the initial temperature, α = 6 W/m^{2}K – the convection coefficient for wheel to air heat transfer, A = 1.307 m^2 – the area of outer wheel surface, V = 0.0361 m^3 – the volume of wheel, ρ = 7850 kg/m^3 – the density of wheel, c = 0.461·10^3 kJ/kgK – the heat capacity, and τ [s] – the time.

Taking into account time period from the moment of wheel positioning (t_p = 250 °C) to the moment of completing the first welded layer (t_p = 3600 seconds – average time for deposition of one layer), and heat transfer from wheel to the ambient air (t_0 = 18 °C), one can calculate the temperature:

$$t=(t_p-t_0)\mathrm{e}^{-\frac{\alpha A\tau}{V\rho c}}+t_0=(250-18)\mathrm{e}^{-\frac{6\cdot 1.307\cdot 3600}{0.0361\cdot 7850\cdot 0.461\cdot 10^3}}+18=203\ ^\circ\mathrm{C} \tag{6}$$

Convection heat is then:

$$Q=\bar{\alpha}A(t-t_0)\tau \tag{7}$$

To determine Nusselt number for natural convection from horizontal cylinder to the still air one can use [9]:

$$\mathrm{Nu}=c'(\mathrm{Gr\ Pr})^{n'}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_z}\right)^{0.25} \tag{8}$$

Physical characteristics of air at average temperature t_f = 20 °C are [9]:

$$\alpha=2.59\cdot 10^{-2}\ \mathrm{W/mK},\qquad \nu=15.06\cdot 10^{-6}\ \mathrm{m^2/s},\qquad \mathrm{Pr}=0.703$$

Prandtl number for air at temperature t_z = 250 °C is Pr$_z$ = 0.677, [9].
Coefficient of air volume extension is:

$$\beta=\frac{1}{t_f}=\frac{1}{293}\,[\mathrm{K}^{-1}] \tag{9}$$

By multiplying Grashof and Prandtl numbers yields:

$$\mathrm{Gr\ Pr}=\frac{\beta g d^3\Delta T}{\nu^2}=\frac{\frac{1}{293}\cdot 9.81\cdot 0.205^3\cdot 232}{(15.06\cdot 10^{-6})^2}=292\ 508\ 585$$

For Gr Pr = 1·10^9, c' = 0.5 and n' = 0.25, so that:

$$\mathrm{Nu}=c'(\mathrm{Gr\ Pr})^{n'}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_z}\right)^{0.25}=0.5\cdot 292\ 508\ 584.52^{0.25}\left(\frac{0.703}{0.677}\right)^{0.25}=66.15 \tag{10}$$

$$\bar{\alpha}=\frac{\overline{\mathrm{Nu}}\,\lambda}{d}=\frac{66.15\cdot 2.59\cdot 10^{-2}}{0.205}=8.4\ \mathrm{W/m^2K} \tag{11}$$

Now, the output heat is:

$$Q_o = \bar{\alpha} A(t - t_0)\tau = 8.4 \cdot 1.307(250 - 203)3600 = 1856 \text{ kJ} \tag{12}$$

The total heat, which is left in the wheel during welding of one layer, is equal to the difference of the input and output heat:

$$Q_{tot} = Q_i - Q_o = 13\,681 - 1\,856 = 11\,825 \text{ kJ} \tag{13}$$

Finally, one can calculate wheel temperature after welding of one layer:

$$Q = \bar{\alpha} A(t - t_0)\tau, \qquad t = 540\ ^\circ\text{C} \tag{14}$$

Figure 2. The FLIR P640 thermovision camera

Experimental measurements

Temperature was measured by using thermovision camera FLIR P640, fig. 2, with following basic characteristics: measuring range: –40 °C to +2000 °C, accuracy ±2 °C.

Typical infrared images are shown in fig. 3 after first welding pass and in fig. 4 after welding has been completed.

Discussion

One can notice that the maximum temperature is almost the same as calculated temperature, 539.3 °C in fig. 4(a), obtained immediately after welding of first layer was finished, *vs.* 540 °C, as obtained analytically, eq. (14). Anyhow, one should keep in mind that calculated value is an average value for the whole wheel, whereas measured values indicate local temperature, in a small region, as shown in figs. 3 and 4. Therefore, more realistic comparison is with average value, ~460 °C, fig. 4(a), indicating significant difference, probably caused by neglecting radiation effects and temperature dependence of material thermomechanical properties.

Anyhow, since the aim of this paper was not only to evaluate the accuracy, but also the applicability of analytical calculation, one should also notice, from the point of view of temperature after welding of first layer, being well above 250 °C, that one can use simple heat transfer analysis as the first approximation.

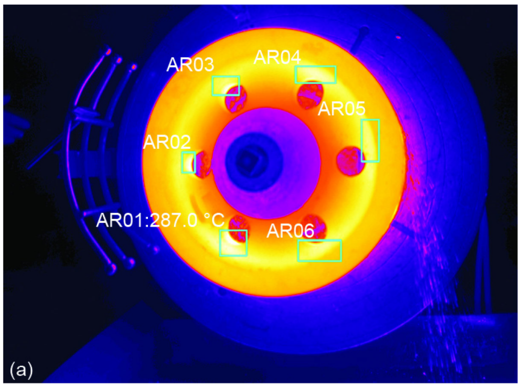
Conclusions

Based on the results presented in the paper, the following conclusions can be made.

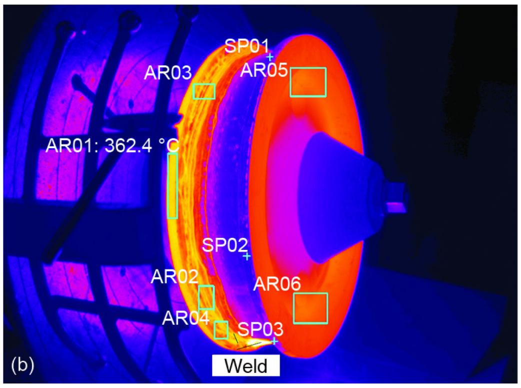
- Calculated temperature has higher values than the measured ones, if compared with the average value (540 °C *vs.* 460 °C), probably because of radiation effects and temperature dependence of thermomechanical material properties, which have been neglected. Accuracy of such calculation is not very high, but it is still applicable in cases such as repair welding and evaluation of preheating temperature.
- Analytical calculation should be improved, so that radiation is taken into account, even though procedure would become more complicated. Anyhow, dependence of thermome-

chanical material properties on temperature can not be taken into account, except by numerical methods, since the equations become non-linear.

IR information	Value
Date of creation	10/2/2013
Time of creation	7:57:22 a. m.
Label	Value
AR01 : max	287.0 °C
AR02 : max	276.4 °C
AR03 : max	274.6 °C
AR04 : max	268.2 °C
AR05 : max	260.1 °C
AR06 : max	262.2 °C



IR information	Value
Date of creation	10/2/2013
Time of creation	7:59:56 a. m.
Label	Value
SP01	105.2 °C
SP02	81.6 °C
SP03	138.3 °C
AR01 : max	362.4 °C
AR02 : max	357.1 °C
AR03 : max	352.8 °C
AR04 : max	367.1 °C
AR05 : max	289.7 °C
AR06 : max	285.3 °C



IR information	Value
Date of creation	10/2/2013
Time of creation	8:00:39 a. m.
Label	Value
SP01	90.1 °C
SP02	80.0 °C
SP03	126.0 °C
AR01 : max	433.4 °C
AR02 : max	386.1 °C
AR03 : max	340.5 °C
AR04 : max	344.1 °C
AR05 : max	348.9 °C
AR06 : max	346.2 °C

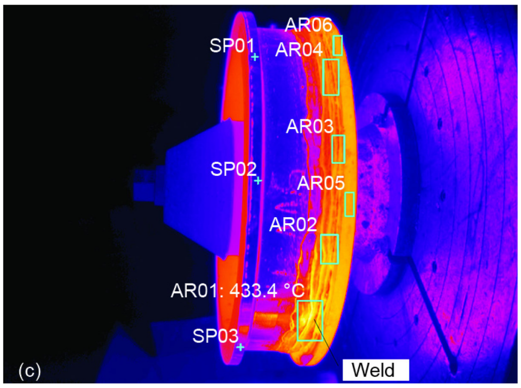
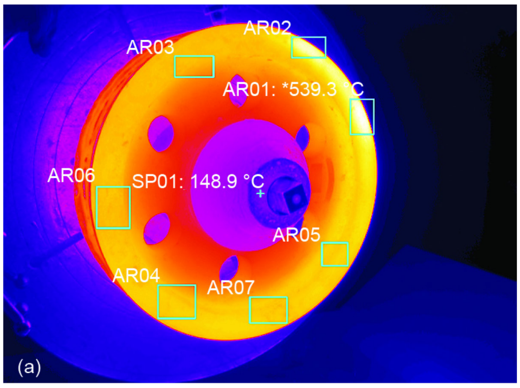
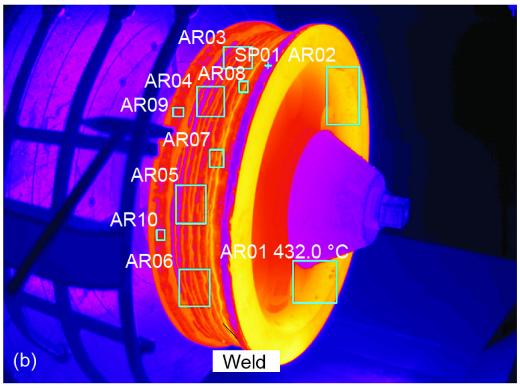


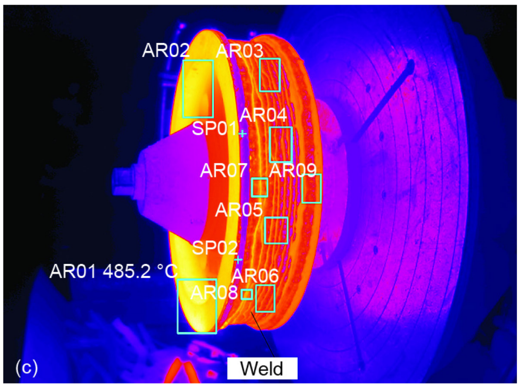
Figure 3. Thermovision image after several welding passes:
(a) immediately after,
(b) ~150 seconds afterwards, and
(c) ~190 seconds afterwards (*for color image see journal web site*)



IR information	Value
Date of creation	10/2/2013
Time of creation	12:45:44 p. m.
Label	**Value**
AR01 : max	539.3 °C
AR02 : max	521.4 °C
AR03 : max	424.0 °C
AR04 : max	440.3 °C
AR05 : max	446.1 °C
AR06 : max	427.4 °C
AR07 : max	441.5 °C



IR information	Value
Date of creation	10/2/2013
Time of creation	12:50:20 p. m.
Label	**Value**
SP01	186.0 °C
SP02	207.8 °C
AR01 : max	432.0 °C
AR02 : max	442.2 °C
AR03 : max	361.2 °C
AR04 : max	351.2 °C
AR05 : max	362.2 °C
AR06 : max	386.8 °C
AR07 : max	409.8 °C
AR08 : max	396.9 °C
AR09 : max	315.0 °C
AR010 : max	282.4 °C



IR information	Value
Date of creation	10/2/2013
Time of creation	12:50:01 a. m.
Label	**Value**
SP01	157.9 °C
SP02	176.9 °C
AR01 : max	485.2 °C
AR02 : max	449.8 °C
AR03 : max	353.6 °C
AR04 : max	377.3 °C
AR05 : max	364.7 °C
AR06 : max	356.8 °C
AR07 : max	409.8 °C
AR08 : max	396.5 °C
AR09 : max	348.6 °C

Figure 4. Thermovision image after welding of one layer:
(a) immediately after,
(b) and (c) ~5 minutes afterwards (*for color image see journal web site*)

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