Neural Network Prediction of Hardness in HAZ of Temper Bead Welding Using the Proposed Thermal Cycle Tempering Parameter (TCTP)

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A new thermal cycle tempering parameter (TCTP) to characterize the tempering effect during multi-pass thermal cycles has been proposed by extending the Larson-Miller parameter (LMP) to non-isothermal heat treatment. Experimental results revealed that the hardness in synthetic HAZ of low-alloy steel subjected to multi-pass tempering thermal cycles has a good linear relationship with the TCTP. The new hardness prediction system was constructed by using a neural network taking into consideration of the tempering effect during multi-pass welding, estimated by using the TCTP. Based on the thermal cycles numerically obtained by FEM and the experimentally obtained hardness database, the hardness distribution in HAZ of low-alloy steel welded with temper bead welding method was calculated. The predicted hardness was in good accordance with the experimental results. It follows that our new prediction system is effective for estimating the tempering effect in HAZ during multi-pass welding and hence enables us to assess the effectiveness of temper bead welding.

KEY WORDS: hardness; tempering; temper bead welding; low-alloy steel; FEM.

1. Introduction

Pressure vessels are in general fabricated from steels with excellent mechanical properties. Low-alloy steel ASTM A533B possessing superior low-temperature toughness and weldability is typically used as the material for pressurized water reactor (PWR) vessels in nuclear power plants. However, the excellent mechanical properties of the base metal will be altered by the thermal cycles imposed by welding processes, and an increase in hardness always occurs in the heat affected zone (HAZ) of the welds. Serious damage may occur in some cases in the coarse grained heat affected zone (CGHAZ). Therefore, post weld heat treatment (PWHT) is normally required to eliminate the residual stress and decrease the hardness.

However, PWHT is sometimes difficult to perform in operation when repairing large-scale structures. In practice, the temper bead welding technique is an effective repair welding method instead of PWHT. Temper bead welding is a kind of multi-pass welding, in which the tempering effect is caused by the heat arising from the following multilayer weld thermal cycles. To achieve the required tempering effect during temper bead welding, it is very important to select the proper thermal cycle. Hardness is one of the key criteria to evaluate the tempering effect in temper bead welding. Hardness in the HAZ is affected by various factors such as peak temperature and cooling rate during the weld thermal cycle and the number of tempering thermal cycles. In the present study, the hardness prediction system has been constructed using a neural network that can process the complex data involved. The proposed hardness prediction system has been verified with comparing the predicted hardness with the measured one in HAZ when temper bead welding is applied.

2. Experimental

The chemical compositions of the low-alloy steel A533B and filler material Inconel690 used are shown in Table 1. Samples of low-alloy steel (5x5x5 mm) were heated by a high frequency induction heating device to synthesize the as-welded and temper-processed HAZs. The isothermal and thermal cycle conditions for the tempering process simulating a CGHAZ are illustrated in Fig. 1. The first cycle, with a peak temperature (Tp) of 1350°C followed by water quench (or cooling at 30°C/s or 3°C/s), was used to simulate the as-welded CGHAZ. The second cycle was used to simulate the tempering process; therefore, the Tp of the second cycle was varied from 400°C to 650°C, lower than Ac1 (670°C). For the isothermal tempering heat treatment (Fig. 1(a)), the holding time was varied from 5 s to 1 hr, followed by water quench. For tempering during the thermal cycles (Figs. 1(b) and 1(c)), the holding time at the peak temperature was 1s, and the cooling rate (CR) varied from 3 to...
It should be noted that there are double tempering thermal cycles in Fig. 1(c).

Figure 2 illustrates four types of thermal cycle patterns to simulate the thermal cycles in HAZ of temper bead welding with consistent layer technique. Fig. 2(a) shows the type of single thermal cycle, marked as 1-cycle. Fig. 2(b) presents the type of double thermal cycle, which is marked as 2-cycle. Figs. 2(c) and 2(d) illustrate the types of 1-cycle+temper and 2-cycle+temper, respectively. The thermal cycle conditions are shown in Table 2. Here, $T_{pi}$ is the peak temperature of the $i$th pass thermal cycle, and $CR_i$ means the cooling rate from 800°C to 500°C of the $i$th pass thermal cycle. When the $T_p$ of the thermal cycle is lower than 800°C, the cooling rate at 400°C is taken as CR. In 1-cycle, $T_{p1}$ was ranged from 400°C to 1350°C, which covered the temperature range of HAZ in low-alloy steel. In the other 3 types of thermal cycle, $T_{p1}$ and $T_{p2}$ were higher than $A_1$, which were used to simulate the CGHAZ, FGHAZ and ICHAZ. Therefore, $T_{p1}$ and $T_{p2}$ varied from 670°C to 1350°C. For the tempering thermal cycle, tempering temperature is lower than $A_1$, thus it was changed in the range of 400°C–650°C. In all thermal cycles, $CR_i$ covered all the possible cooling rate range in HAZ, therefore it varied from the lowest 3°C/s to the highest water quenching.

The multi-pass welded samples (100×35×150 mm) were produced by TIG welding with the welding conditions shown in Table 3. The temper bead welding was performed using consistent layer technique. The section surfaces of 1-layer (A1), 3-layer (A3) and 6-layer (A6) are cut from the multi-pass welded sample. The Vickers hardness was measured in the section of the specimens after polishing and etching with 3% nital solution. The Vickers hardness measurement was performed at a load of 9.8 N, and the mean values were taken after excluding the maximum and minimum values from each multiple measurement. The thermal cycles in temper bead welding were calculated using FEM software developed by the authors specifically for welding simulation.

### 3. Hardness Distribution in HAZ of Temper Bead Welding

#### 3.1. Experimentally Measured Hardness

Figs. 3(a), 3(b) and 3(c) illustrate the section macrostructures of A1 (1 layer-3 pass welds), A3 (3 layer-12 pass welds) and A6 (6 layer-19 pass welds), respectively. The hardness distributions in the CGHAZ along the dotted curve in Figs. 3(a), 3(b) and 3(c) are shown in Fig. 3(d). The hardness in CGHAZ after 1-layer welding are high and uneven depending upon the position, while the hardness after 3-layer and 6-layer welding are relatively even and much low-
er than the former. The average hardness in CGHAZ after 1-layer welding is 367 HV. It respectively decreased to 266 HV and 260 HV, after 3-layer and 6-layer welding. This indicates that temper bead welding is an effective technique to decrease the hardness and improve the mechanical properties of HAZ.\textsuperscript{1,5)}

Figure 4 shows the microstructures in CGHAZ after 1-layer and multi-layer welding. The microstructure of CGHAZ after 1-layer welding mainly consists of martensite, which is the reason for the high hardness. After 3-layer and
6-layer welding, the microstructure changed to tempered martensite, with fine carbides precipitated on the martensite laths, and the amount of the precipitated carbides increased after 6-layer welding than 3-layer welding. Such tempered martensite resulted in the decreasing hardness.

The hardness and the microstructure in HAZ of temper bead welding are determined by the thermal cycles in HAZ, therefore the multi-thermal cycles in HAZ has been subjected to the following detailed analysis.

3.2. Thermal Cycle Analysis in HAZ of Temper Bead Welding

For 1-layer welding, there are 2 kinds of thermal cycles occurred in HAZ of multi-pass welding: (a) 1-cycle, which is affected by 1-pass welding; (b) 2-cycle, in the middle overlapped region of 2-pass welding.

Figure 5 presents a schematic illustration of temper bead welding produced by consistent layer technique. In this technique, HAZ of the first layer is only tempered but has not retransformed by the subsequent layers, because this technique places the Ac1 retransformation line of the second layer welding within the fusion zone produced by the first layer welding, as shown in Fig. 5(b). Because there are only tempering thermal cycles from the 2nd layer welding in consistent layer technique, the possible thermal cycles after multi-layer welding are 1-cycle+temper and 2-cycle+temper. Therefore, the thermal cycles in HAZ of temper bead welding produced by consistent layer technique are most simply classified as the following four types: (1) 1-cycle; (2) 2-cycle; (3) 1-cycle+temper; (4) 2-cycle+temper, as shown in Fig. 2.

For the 1-cycle, the hardness is mainly dependent on two factors: Tp and CR. The 2-cycle is more complicated, with four factors governing the hardness: Tp1 and CR1 of the first thermal cycle, and Tp2 and CR2 of the second thermal cycle. Besides of these factors, the temper cycles are also included in 1-cycle+temper and 2-cycle+temper. As HAZ of the first layer will be subjected to many temper thermal cycles from the upper layers in multi-pass welding, it should be necessary to assess the tempering effect of all the temper thermal cycles in a simple way. Hence, the assessment method of the tempering effect during temper thermal cycles will be discussed as below.

4. Proposal of Thermal Cycle Tempering Parameter (TCTP)

When considering long-term operation in the tempering temperature range, the Larson-Miller parameter (LMP) is a useful means to predict the change in properties of a material. The LMP is derived based on the Arrhenius rate equation, and is expressed as a function of time and temperature:

\[ LMP = T \left( \log t + C \right) \] .......................... (1)

where T is the temperature in Kelvin, t is the time in hours and C is a material specific constant often approximated as 20 for steel. It should be noted that LMP can be used only for isothermal heat treatment with constant tempering temperature, for the case in Fig. 1(a). But it cannot be applied for tempering during thermal cycle processes such as those shown in Figs. 1(b) and 1(c).

4.1. Proposal of TCTP by Extending LMP

To apply LMP to temper thermal cycle process, the thermal cycle was divided into small increments where each increment could be regarded as an isothermal heat treatment with a “short” holding time, as shown in Fig. 6. To decrease the error, the average temperature of the thermal cycle during the time increment is used as the temperature for the “short” isothermal heat treatment. The overall tempering effect during the thermal cycle process is considered as the sum of the “short” isothermal heat treatments.

The LMP for the overall thermal-cycle heating process is not simply the cumulative total of each isothermal heat treatment, because LMP is not a linear function of time and temperature. Therefore, a new method has been proposed in this paper to calculate the temper parameter during a thermal-cycle process.

As illustrated in Fig. 7, the temper parameter of the first segment at T1 with holding time t1 is equal to that at T2 with equivalent holding time t1,2, shown as

\[ P_1 = T_1(20 + \log t_1) = T_2(20 + \log t_1,2) \] .......................... (2)

Thus, the equivalent holding time t1,2 at T2 can be obtained as

\[ t_1,2 = 10^{\frac{P_1 - 20}{T_1}} - 1 \] .......................... (3)

Then the temper parameter of the combined first and second segments can be expressed as

\[ P_2 = T_2[20 + \log(t_1,2 + t_2)] \] .......................... (4)

Similarly, the temper parameter of the combined first and second segments is equal to that at T3 with equivalent holding time t2,3, shown as follows:

\[ P_3 = T_3[20 + \log(t_2,3 + t_3)] \] .......................... (5)

Fig. 5. Division of temper cycle to very small time increments.

Fig. 6. Division of temper cycle to very small time increments.

Fig. 7. Schematic illustration of TCTP calculation.
The temper parameter during thermal cycle calculated by this newly proposed method is termed as “Thermal cycle tempering parameter (TCTP)”.

### 4.2. Experimental Validity of TCTP

**Figure 8** shows the relationship between hardness of the specimens and TCTP of the second and third tempering thermal cycles when the specimens were initially heated to 1350°C followed by three different cooling conditions (Fig. 1). A good linear relationship can be seen between the hardness of the specimens and TCTP. Furthermore, the hardness of the isothermal heat-treated specimens is also on the same line. This shows that the newly proposed TCTP can be applied to evaluate quantitatively the tempering effect and the hardenability change during both thermal cycle tempering processes and isothermal heat treatment.

It should be noted that when the initial hardness is same, which means the 1st or 2nd thermal cycle before temper cycle is same, the final hardness after temper cycle has the same linear relationship with TCTP. It can be found out from Fig. 8(a). But, if the initial hardness is different, the final hardness after temper cycle also has different linear relationship with TCTP. For example, the slope factors of the lines in Figs. 8(a), 8(b) and 8(c) are different, because the first thermal cycles have the different CR1. This indicates that the hardness after temper cycle is dependent on 2 factors: (1) initial hardness before temper cycles; (2) tempering effect of temper cycles. The former one is decided by the parameters of the 1st or 2nd thermal cycles: Tpi and CRi (i = 1, 2). And the later one can be evaluated by the temper parameter: TCTP. Above all, the hardness after temper cycle is decided by the following parameters: Tpi, CR, and TCTP.

### 4.3. Theoretical Validity of TCTP

Based on Arrhenius’ equation, Inoue13) has defined a tempering parameter (λ-value) to express the degree of tempering and to maintain the equivalence of time and temperature over a wide range of tempering conditions. Although the λ-value can be used to evaluate the tempering effect, it cannot describe the evolution of hardness during tempering and also cannot predict the hardness variation of steels in service with time and temperature. The method also requires calculation of fundamental parameters (for example, activation energy, Q) based on experimental results, which may include experimental errors that affect further calculation.

Hollomon and Jaffé14) proposed that the same hardness could be reached by different tempering history, i.e. by different time-temperature routes assuming that the hardness was a function of the time and the temperature:

\[
\text{Hardness} = f\left[\lambda \exp\left(-\frac{Q}{RT}\right)\right]
\]

They then obtained a relationship between the hardness and a tempering parameter M:

\[
\text{Hardness} = f(M) = f\left[\lambda (c + \log \, t)\right]
\]

This relationship has been widely used to determine the likely outcomes of different tempering conditions in industry.

With regard to creep and stress-rupture, Larson and Miller15) derived the similar Eq. (1) based on the Arrhenius rate equation. The LMP continues to be widely used for correlation of creep and stress-rupture data of various engineering materials. And it has also been used for studying the effect of temperature service on tempering characteristics: hardness, microstructure and notch toughness etc.16,17) However, the LMP cannot be used to evaluate the tempering effect of thermal cycles. Therefore, we extend the LMP to give our proposed TCTP. The TCTP enables the assessment of both isothermal heat treatments and thermal cycles.

It should be noted that Ref. [18] has also proposed an extending LMP calculation method to assess the tempering effect during the multi-pass PWHT. In this calculation, all multi-pass PWHT are converted into a same standard temperature Ts (Eq. (11)), and the overall tempering parameter was expressed in Eq. (12).

\[
P_i = T_i(20+\log t_i) = T_i(20+\log t_{n})
\]
However, as shown in Fig. 9, the additivity method of each isothermal heat treatment time ($t_{si}$) at this standard temperature $T_s$ is inappropriate, which included the holding time error of $t_0$ ($t_0 = 10^{-2}$, $P = T(C + \log t) = 0$, $C = 20$ for the steel). Therefore, the more multi-pass PWHT are included, the more holding time error ($n \times t_0$) would occur. Furthermore, different $P$ value ($\Sigma P_i$) will be given out with different standard temperature $T_s$, which is illustrated in Fig. 10. As for these reasons, it cannot be used for evaluating the tempering characteristics during a thermal cycle.

When a metallurgical phenomenon is caused by a thermal cycle process, it can be considered such as the cumulative set of isothermal process using the “additivity rule”. An additive reaction implies that the total time to reach a particular stage of transformation is obtained by adding the fractions of the time to reach this stage isothermally until the sum reaches unity. It then follows:

$$\int_{t_0}^{t} \frac{dt}{t_i(f_i,T)} = 1 \quad \text{...........................(13)}$$

where $t_i(f_i,T)$ represents the isothermal transformation time for $f = f_i$ at temperature $T$, and $t$ is the total non-isothermal transformation time. The additivity rule (Eq. (13)) has been widely used to predict the phase transformation kinetics of steels and other alloys during continuous cooling from isothermal data. The additivity rule is compatible with isokinetics, where constant kinetic parameters are assumed, for a single transformation with invariable transformation mechanism. The tempering thermal cycle also fits the invariable transformation mechanism. Therefore, the tempering thermal cycle can be divided into small increments where each increment could be regarded as an isothermal heat treatment with a “short” holding time, and the tempering parameter can calculated by the proposed TCTP method using the additivity rule. In summary, TCTP is a useful method to investigate the temperature service on tempering characteristics during a thermal cycle.

5. Prediction System of Hardness in HAZ of Multi-pass Welding

Because the hardness after all kinds of thermal cycles are determined by the parameters: $T_{pi}$, $CR_i$, and TCTP, the prediction systems of hardness are constructed with using a Neural Network (NN), which can process the complex data involved.

5.1. Neural Network

NN is a computational model that simulates the structure and/or functional aspects of biological NNs. In most cases, a NN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. Modern NNs have become useful modeling tools for non-linear statistical data. They are usually used to model complex relationships between inputs and outputs or to find patterns in data.

The radial basis function (RBF) is a powerful technique for interpolation of multidimensional space in a NN. RBFNN typically has three layers: an input layer, a hidden layer with a non-linear RBF activation function and a linear output layer. The hidden layer can be described by a Gaussian basis function:

$$h(x) = \exp\left[-\frac{(x-c)^2}{r^2}\right] \quad \text{.................(14)}$$

where $x$ is the input data, $c$ is the center vector, and $r$ is the Euclidean distance. In the basic form all inputs are connected to each hidden neuron.

The output $O(x)$ of the network is thus

$$O(x) = \sum_{j=1}^{n} w_j h_j(x) = \sum_{j=1}^{n} w_j \exp\left(-\frac{(x-c_j)^2}{r^2}\right) \quad \text{.....(15)}$$

where $n$ is the number of neurons in the hidden layer, $c_j$ is the center vector for neuron $j$, and $w_j$ are the weights of the linear output neuron. The weights $w_j$, $c_j$, and $r$ are determined in a manner that optimizes the fit between $O(x)$ and the data.

5.2. Prediction System of Hardness

In the present study, the thermal cycle parameters ($T_{pi}$, $CR_i$, and TCTP) are the input data, and the hardness is the output data. The validity range of the input parameters for NN is shown in Table 4. Thus, the main question is the

**Table 4. Validity range of input parameters in 4 kinds of hardness prediction systems for neural network.**

| Parameters | $T_{pi}$ (°C) | $CR_i$ (°C/s) | $T_{0}$ (°C) | $CR_0$ (°C/s) | TCTP |
|------------|----------------|---------------|---------------|---------------|------|
| 1-cycle    | 400–1500       | 3–100         | 3–100         | 3–100         |      |
| 2-cycle    | 670–1500       | 3–100         | 670–1500      | 3–100         | 13900–22000 |
| 1-cycle+temper | 670–1500   | 3–100         | 670–1500      | 3–100         | 13900–22000 |
| 2-cycle+temper | 670–1500 | 3–100         | 670–1500      | 3–100         | 13900–22000 |
determination of $w_i$, $c_i$, and $r$, which depend on practical experimental results. Based on the experimentally measured hardness results, the thermal cycle parameters and hardness data were fed into the RBF-NN, and as a result $w_i$, $c_i$, and $r$ were determined. It should be noted that every input data set has produced one weight $w_i$, therefore thousands of weights $w_i$ have been produced according to the thousands of experimental results. By using these obtained constants, the hardness prediction system for multi-pass thermal cycles was constructed.

Fig. 11. Results of hardness prediction system of 1-cycle: (a) 3D figure, (b) 2D-Contour figure.

Fig. 12. Results of hardness prediction system of 2-cycle when $T_{p1} = 1350 \, ^\circ C$, $C_{R1} = 91 \, ^\circ C/s$: (a) 3D figure, (b) 2D-contour figure.

Fig. 13. Results of hardness prediction system of 1-cycle+temper with a constant $TCTP$ of 13947: (a) 3D figure; (b) 2D-contour figure.

Fig. 14. Results of hardness prediction system of 2-cycle+temper when $C_{R1} = 88 \, ^\circ C/s$, $T_{p2} = 950 \, ^\circ C$, $C_{R2} = 90 \, ^\circ C/s$: (a) 3D figure; (b) 2D-contour figure.
Based on plentiful experimental results, a hardness prediction system for these four types of HAZ has been constructed, as illustrated in Figs. 11–14. Figs. 11(a) and 11(b) respectively represent the calculated 3D and 2D-contour figures of the complex relationship between hardness and \( T_p \) or \( CR \) for 1-cycle. In the 2D-contour figure of Fig. 11(b), different hardness ranges are shown in different colors, and the star marks indicate the highest hardness. With this prediction system, the hardness of the steel subjected to any single thermal cycle can be calculated if the \( T_p \) and \( CR \) of the thermal cycle process are known. It means that the hardness in HAZ of 1-pass welding can be calculated with the hardness prediction system of 1-cycle.

Figure 12 shows an example of the hardness prediction system for 2-cycle. In this system, there are four input parameters: \( T_{p1} \) and \( CR_1 \) of the first thermal cycle, and \( T_{p2} \) and \( CR_2 \) of the second thermal cycle. Together with the output hardness, it is a five-dimensional space. To enable visualization of the results, two of these parameters must be fixed. Figs. 12(a) and 12(b) show the 3D and 2D-contour relationship figure between hardness and \( T_{p2}/CR_2 \) of the second thermal cycle, when \( T_{p1} \) and \( CR_1 \) of the first thermal cycle are fixed at 1 350°C and 91°C/s, respectively. Here, all the 2D-contour figures use the same color-hardness scale. This data shows that \( T_{p2} \) and \( CR_2 \) of the second thermal cycle have a strong influence on the properties and microstructure of the steel after multi-pass welding, which is similar to previous results.8–10)

Figure 13 presents an example of the hardness prediction system for a 1-cycle+temper. There are three variable parameters: \( T_{p1} \) and \( CR_1 \) of the first thermal cycle, and TCTP of the following temper cycles with peak temperature lower than \( Ac_1 \). The relationship between hardness and \( T_{p1}/CR_1 \) of the first thermal cycle is shown in Fig. 13, with a constant TCTP value of 13947.

Among these four systems, 2-cycle+temper is the most complicated for hardness prediction. In this system, five parameters have been included: \( T_{p1} \) and \( CR_1 \) of the first thermal cycle, \( T_{p2} \) and \( CR_2 \) of the second thermal cycle, and TCTP of the following temper cycles. Figure 14 shows one example of the relationship between hardness and \( T_{p2}/TCTP \), when \( CR_1, T_{p1} \) and \( CR_2, T_{p2} \) are fixed. It should be noted that the hardness is not determined only by the 2 input parameters presented in Figs. 12–14, in fact it is determined by all the input parameters. With these 4 types of hardness prediction systems, hardness in HAZ of low-alloy steel produced by multi-pass welding using consistent layer technique can be calculated with the hardness prediction system of 1-cycle.

### 5.3. Effectiveness of Hardness Prediction System

In order to verify the effectiveness of the hardness prediction system, samples heated with arbitrary thermal cycles have been used to survey the hardness. The details of the arbitrary thermal cycle conditions are shown in Table 5. Twenty thermal cycles were chosen, which included two 1-cycle and 2-cycle, and six 1-cycle+temper and 2-cycle+temper. The hardness of the samples after the arbitrary thermal cycles being applied is compared with the predicted hardness calculated by the formerly constructed NN-hardness prediction system, as illustrated in Fig. 15.

| Parameters | \( T_{p1} \) (°C) | \( CR_1 \) (°C/s) | \( T_{p2} \) (°C) | \( CR_2 \) (°C/s) | Tempering cycle |
|------------|------------------|------------------|------------------|------------------|----------------|
| 1-cycle    | 1300             | 60               | 900              | 42               |                |
| 2-cycle    | 1300             | 57               | 1200             | 38               |                |
|            | 1200             | 51               | 720              | 33               |                |
| 1-cycle+temper | 1300           | 63               | 1300             | 67               | 1200          |
|            | 1200             | 36               | 720              | 37               | 1200          |
|            | 1100             | 50               | 600              | 12               | 500           |
|            | 750              | 10               | 665              | 10               | 600           |
|            | 1300             | 12               | 600              | 12               | 500           |
| 2-cycle+temper | 1300           | 67               | 1300             | 67               | 1200          |
|            | 1200             | 37               | 1200             | 37               | 1200          |
|            | 900              | 17               | 550              | 22               |                |
|            | 750              | 10               | 665              | 10               | 600           |
|            | 1300             | 12               | 600              | 12               | 500           |
|            | 100              | 50               | 600              | 3                | 500           |
|            | 20               | 20               | 600              | 3                | 500           |

* WQ: water quenching.

The horizontal coordinate presents the experimentally measured hardness, and the longitudinal coordinates shows the calculated hardness. There is a good agreement between the calculated hardness and the measured one. According to these, the hardness after any thermal cycles can be calculated using the hardness prediction system, when the thermal cycle parameters are known.

### 6. Prediction of Hardness in HAZ of Temper Bead Welding

#### 6.1. Temperature Analysis in HAZ by FEM

The temperature distributions produced by multi-pass thermal cycles in welds during temper bead welding were calculated using three-dimensional finite element analysis code, developed by the authors specifically for welding simulation.7) The mesh model is the same size with the experimental welding sample, and the welding conditions were the same as the experimental conditions shown in Table 3,
which followed the consistent layer technique. Figures 16(a), 16(b) and 16(c) present the calculated peak temperature distribution in the middle section of 1 layer-3 pass, 3 layer-12 pass and 6 layer-19 pass welds, respectively. Different peak temperatures are presented in different colors.

6.2. Hardness Prediction in HAZ Based on the FEM Simulated Thermal Cycle

Based on the calculated thermal history of every grid node, the hardness at the grid node was calculated. First, the base metal (BM), HAZ and the weld metal (WM) were judged according to the peak temperatures of the multi-pass thermal cycles. If all the peak temperatures are lower than 400°C, the grid node is considered as BM. If any peak temperature of the thermal cycle is over 1500°C, then it is classified as WM. All the others, with at least one peak temperature during the thermal cycles between 400°C and 1500°C, are considered to be HAZ, which is the target region to be calculated. Within this part of HAZ, the thermal cycles of the grid nodes are also classified into four types: 1-cycle, 2-cycle, 1-cycle+temper and 2-cycle+temper. For the multi-pass thermal cycles with temper thermal cycles, TCTP of the temper thermal cycles is calculated using the newly proposed TCTP calculation method. Following this, the original parameter $T_{pi}/CR_i$ and the calculated TCTP are fed into the NN prediction systems, and the hardness at every grid node is calculated.

On the basis of the predicted hardness at every grid node, the visual hardness distribution in the HAZ is shown as color chart maps in Fig. 17. Figure 17(a) illustrates the hardness distribution in HAZ of 1-layer-3 pass welding. Besides the red WM and grey BM regions, the hardness in HAZ is shown with rainbow colors depending on the different hardness levels. There are some hard HAZ ranges with the hardness higher than 350 in the HAZ of 1-layer welding. Compared with it, the hardness was greatly decreased after 3-layer and 6-layer welding and the hard HAZ range has disappeared, as shown in Figs. 17(b) and 17(c). This illustrates the effectiveness of temper bead welding in decreasing hardness.

6.3. Validity of Hardness Prediction System

The predicted hardness and the experimentally measured results for the HAZ of A533B low-alloy steel after 1-layer, 3-layer and 6-layer welding are shown in Figs. 18(a), 18(b) and 18(c). The hardness is measured along the yellow dotted line, 1.5 mm from the sample surface. The blue points are the experimentally measured hardness, and the red points are the calculated hardness using our NN prediction systems, based on the FEM simulated thermal history. The predicted hardness is in good accordance with the experimentally measured hardness. It follows that the proposed hardness prediction system is useful and effective for estimating the tempering effect in temper bead welding.
Through this method, the hardness can be predicted before the actual temper bead welding. If the calculated hardness in HAZ is higher than the critical value, the welding conditions would be modified. Thus, the appropriate welding conditions can be selected before the actual welding. In the present study, low-alloy steel A533B was targeted. However, the hardness prediction method can be applied for other material with only the hardness data-base being changed. Therefore, the presently proposed method is useful for assessment of tempering effect of multi-pass welding of any steels. It is useful for the repair welding for large structures.

7. Conclusions

A NN-based prediction system for the hardness of HAZ in low-alloy steel when temper bead welding is applied has been investigated. The following conclusions can be drawn:

1) The hardness of specimens subjected to multi-pass thermal cycles has a good linear relation with the newly developed thermal cycle tempering parameter (TCTP). The TCTP is an extension of the Larson Miller parameter which includes the effects during multi-pass thermal cycles.

2) The NN-based system for hardness prediction was constructed with experimentally obtained hardness data. On the basis of the FEM simulated thermal cycle parameters, the hardness distribution in HAZ of temper bead welding was predicted using the NN.

3) The predicted hardness was in good accordance with the experimental results. It follows that the proposed hardness prediction system is effective for estimating the tempering effect in temper bead welding.

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