Control of mechanical properties in structural steel welds by numerical simulation of coupling among temperature, microstructure, and macro-mechanics

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Abstract

The mechanical characteristics of steel welded structures such as tensile strength or fracture toughness depend on welding conditions, and multiple welding heat cycles particularly affect the joint performance. It should be controlled under consideration of the microscopic and macroscopic behaviors in materials. In this paper, numerical simulation method of coupling analysis of temperature, microstructure, and stress–strain fields has been developed and applied to investigate the effects of heat input and interpass temperature at multi-pass welded joint of beam-to-column connections on the strength and fracture. Tensile test, Charpy impact test, and three-point bending CTOD test are performed by using welded joint specimen fabricated with various welding conditions. The results of experiments actually show that there exists a welding condition that decreases the joint performance. Three-dimensional thermal elastic–plastic finite-element analysis is developed and performed by using heat source movement and considering phase transformation effect in order to evaluate the proportion of microstructure, distribution of hardness and strength. The parameters of heat input, interpass temperature, and welding direction are changed in the analyses, and the results are used for the consideration of the effect of multiple heat cycles on joint performance. The analytical and the experimental results have shown that controlling heat input and interpass temperature are important features to assure the integrity of welded joints in beam-to-column connections of steel framed structures, and that mechanical properties of the weld metal and the heat-affected zone could be predicted and controlled by using numerical simulation.

Keywords: Welding heat cycle; Joint performance; Multiple welded joint; Welding deposition sequence; Interpass temperature; Heat input; Cooling rate; Mechanical properties; Numerical simulation; Coupling analysis

1. Introduction

Welded joints in beam-to-column connections of steel framed structures sometimes become a critical position for failure when enormous earthquake might occur. The Northridge and the Great Hanshin–Awaji Earthquakes have actually induced extensive damage in beam-to-column welded joints [1,2]. For assuring the integrity of welded structures, it is important to prevent weld defect in the weld metal and to secure the accuracy of the fabricating objects. Furthermore, ensuring mechanical properties of the welded joint such as tensile strength and fracture toughness should be considered in the fabrication. Since the mechanical properties of welded joints are remarkably influenced by the complex thermal cycle due to welding, it is essential to clarify an appropriate controlling procedure of the thermal cycle in the welding of structural steels. Performance of a welded joint is affected by the coupling of heat cycles, microstructural changes, and macro-mechanics such as stress–strain fields. It is well known that the performance of welded joint depends on welding conditions of heat input, interpass temperature, or sequence of welding pass deposition [3–9]. Multiple welding heat cycles particularly affect the joint strength and toughness, but the relation between the actual welding conditions and joint performance such as tensile strength and fracture toughness in welded joints of beam-to-column connections is not well clarified [4–6,9]. A lot of experimental approaches have been applied to the evaluation of joint performance in order to correlate welding conditions and joint characteristics [3, 6,7], and analytical procedure of the evaluation is much...
effective for the consideration of the complicated weld phenomena and furthermore for the prediction of mechanical properties of welded joints [10–18]. Numerical simulation is more convenient in the evaluation [4,5,9,17, 18]. Therefore, the effects of heat input and interpass temperature at multi-pass welding on the characteristics of strength and fracture in welded joints of the beam-to-column connections are studied in this paper by using and comparing with both experimental and analytical approaches. Numerical simulation is done by developing a coupling analysis method among temperature, microstructure, and stress—strain fields. Mechanical and fracture tests such as tensile test, Charpy impact test, and three-point bending test are performed by using welded joint specimen fabricated with various welding conditions. The parameters of heat input, interpass temperature, interval time, welding pass sequence and depositing direction are considered for fabrication. And three-dimensional thermal elastic—plastic finite-element analysis is performed by using the moving heat source with weld metal deposition and by considering coupling effects of phase transformation and temperature for physical and mechanical properties. Temperature and stress histories are simulated during all welding process and the analytical results are used for the interpretation of the experimental results. Mechanical properties of the weld material and the heat-affected zone are predicted by numerical simulation of coupling analysis between temperature and microstructure. It is shown that considering and controlling heat input and interpass temperature is much important to assure and control the quality of welded joints in beam-to-column connections of steel framed structures by using results of the numerical simulation of coupling phenomena among temperature, microstructure, and macro-mechanics.

2. Mechanical and fracture tests in welded joints

2.1. Welded joints and test specimen

Beam-to-column connections of steel framed structures are fabricated by a gas metal arc welding. Many failures occurred in the butt-welded joint between the diaphragm of the box column and the flange of the H-shaped beam in recent earthquakes [1,2]. Therefore, a welded joint specimen was chosen as shown in Fig. 1. This figure shows the configurations of a beam-to-column structure and a welded joint specimen, which was extracted from the actual structure. Weld length is set to 200 or 300 mm at continuous welding (200 C) and set to 200 mm at intermittent welding (200 I). Total welding time for specimen 200 I became much larger than that of 200 and 300 C, and the specimen 200 C has the highest interpass temperature. Interpass temperature of the intermittent welding measured at a point of 10 mm apart from the edge of V-shaped groove at the center along weld line on the flange upper surface is set to within 350 °C, which is the maximum temperature recommended the Japanese Architectural Standard Specification for Steel Works (JASS 6) [19]. Interpass temperature of the JASS 6 was empirically decided but it has not been always validated in all cases [3,6]. Material for the base metal is 490 MP-class high tensile strength steel JIS SN490B and CO2 gas arc semiautomatic welding with filler wire JIS YGW11 of diameter 1.2 mm was done. L-shaped flux end tab was used at the edge of weld metal. Three registered welders by JASS 6 performed all welding process including heat input by the most appropriate conditions that he usually applies to the actual structures. The specimen for experiments were prepared by using the welded joints fabricated with various welding conditions. Mechanical and fracture tests of tensile test, Charpy impact test, and three-point bending CTOD test were performed. Round-bar tensile specimen was cut from the weld metal near the root side and near the final pass-side. The position of root notch of Charpy impact test was set to the weld metal, fusion line, and heat-affected zone. And the crack tip along thickness direction was prepared for the three-point bending CTOD specimen.

2.2. Results of experiments

The relation between tensile mechanical characteristics and the position through thickness direction in the weld metal is shown in Fig. 2. Both yield stress and tensile
strength are smaller near the last pass-side surface than those near the root surface regardless of weld pass deposition. Intermittent welding enables to assure higher tensile characteristics than continuous welding. Decreasing rate of yield stress by continuous welding is much higher than that of tensile stress. It is considered that two factors affect at the same time: softening effect by interpass temperature rise near the last pass-side surface, and hardening effect by multiple heat cycles near the root surface. Fig. 3 shows the effects of weld length and interpass temperature on mechanical properties. Continuous welding and short weld length decrease yield stress. This is because the interpass temperature increases when continuous welding is done in the short weld length specimen.

Turning-back welding operation particularly might decrease joint strength. Effects of weld length and interpass temperature on absorbed energy are shown in Fig. 4. There is a tendency to decrease the absorbed energy in the weld metal and near the fusion line when interpass temperature becomes higher. Fig. 5 shows the effects of weld length and interpass temperature on critical CTOD. High interpass temperature induces short critical CTOD value. However, the dispersion of microstructure and toughness due to the complicated multiple heat cycles should be considered in the evaluation. The results of a series of the experiments actually show that there exists a welding condition which decreases the joint performance. All results from Figs. 2 to 5 are, however, confirmed to be still acceptable for the actual usage to beam-to-column connection, but some values are of course very low.
3. Coupling simulation of welding heat cycles

Experimental results show that high interpass temperature decreases the joint performance of mechanical and fracture behavior. It is, however, difficult to clarify the relation between interpass temperature and the condition of actual welding process. The reason is because the interpass temperature for evaluating joint performance has not been strictly defined yet. Measuring point by JASS 6 gives only one temperature in the heterogeneous temperature distribution of the whole welded joint. Temperature in the weld metal or at the edge of weld line differs from that by JASS 6 position. The consideration is also important to clarify the meaning of the interpass temperature recommended by JASS 6. Numerical analysis is much effective to solving these tasks.

3.1. Coupling analysis method

Three-dimensional heat conduction and thermal elastic-plastic analysis has been newly developed and performed by using heat source movement with the deposition of welding pass and by considering the phase transformation effect. Temperature, microstructure and stress-strain histories are numerically simulated in the coupling analysis by considering the interaction, as shown in Fig. 6. Thermal stress by temperature distribution, microstructural transformation due to temperature change, and transformation stress are particularly important in weld phenomena. Enhanced model of phase transformation from Johnson–Mehl–Avrami law [11–13] and Koistinen–Marburger law [14] with continuous heating/cooling transformation diagram is used in the analysis [15–17]. Fig. 7 shows an example of the phase transformation from ferrite–pearlite to austenite during heating process considering heating rate. Phase transformation phenomena changes due to heating or cooling rate and is considered in the numerical analysis. Non-linear finite-element analysis is adopted in the coupling analysis among temperature, microstructure, and macro-mechanics such as stress-strain behavior.

3.2. Model of multi-layered welded joint for numerical analysis

A lot of failures in brittle manner occurred in the butt-welded joint between the diaphragm and the flange of the H-section beam in the Northridge and Hanshin-Awaji Earthquakes. The model of a butt-welded joint, shown in Fig. 8, is chosen as a typical and simple example in order to characterize the analytical results appropriately. The model in this analysis shows the simplified configuration of a part of the beam-to-column connection in the practical steel framed structures, which is most common in Japan. Plate width is set to 200 mm and is equivalent of weld length. Measuring point of the interpass temperature recommended by JASS 6 is also shown in the figure. Interpass temperature by JASS 6 is evaluated at a point of 10 mm apart from the edge of V-shaped groove at the center along weld line on the flange upper surface [19].

3.3. Material properties used

Numerical simulation is performed on the assumption that the material properties of weld metal and base metal are the same. The same continuous cooling transformation diagram and physical properties are adopted for base metal and weld metal. Physical properties of thermal conductivity, specific heat, heat transfer coefficient, and CCT diagram...
with microstructural dependant are shown in Fig. 9. Material properties are given considering not only microstructure but also temperature dependency. Four microstructure, ferrite–pearlite, bainite, martensite, and austenite are used in the analysis and the material property in each microstructure is defined. Cooling curves, elapsed time from 800 to 500 °C, and the proportion of each microstructure at finishing transformation are also described in Fig. 9(d). Actual welded joint of the beam-to-column connection in steel framed structure is received multiple welding heat cycles, therefore material properties near weld zone change by each weld pass because the maximum temperature and cooling rate of each heat cycle change in each weld pass. Determining all material properties during welding process is too complicated and the initial material properties at each temperature and microstructure are assumed to be kept during all welding process in the present analysis, e.g. CCT diagram is prepared at the condition of the maximum temperature fixed.

3.4. Calculation of Vickers hardness

Vickers hardness is used as an indicator of the strength of welded joints. Vickers hardness of each phase of ferrite–pearlite, bainite, and martensite, HvF, HvB and HvM, respectively, is calculated by the following equations which contains the chemical composition and the cooling rate at 700 °C, VR [20,21].

\[
H_{vF} = 62 + 223C + 15Si + 30Mn + 21Ni + 23Cr + 19Mo + 26V
\]  
(1)

\[
H_{vB} = -323 + 185C + 330Si + 153Mn + 65Ni + 144Cr + 191Mo + \log_{10} VR (89 + 53C - 55Si)
\]  
(2)

\[
H_{vM} = 127 + 949C + 27Si + 11Mn + 8Ni + 16Cr + 21\log_{10} VR
\]  
(3)

Table 1 shows the chemical composition of the 490 MPa-class high tensile strength structural steel JIS SN490B used for the calculation of Vickers hardness. Vickers hardness of a certain microstructure caused in welded joints Hvall is calculated in Eq. (4).

\[
H_{vall} = p_FH_{vF} + p_BH_{vB} + p_MH_{vM}
\]  
(4)

Here, \(p_F, p_B, p_M\): proportion of microstructure of ferrite, bainite, and martensite, respectively. Distribution of Vickers hardness near weld zone is thus obtained by using the results of numerical simulation of the coupling analysis and the initial chemical composition of the material.

![Fig. 9. Material properties used for heat conduction analysis, (a) thermal conductivity, (b) specific heat, (c) heat transfer coefficient, (d) CCT diagram.](image-url)
3.5. Welding conditions

In order to clarify the effect of welding procedure resulting in the change of interpass temperature, three conditions as in Table 2 are selected. The number of welding layer is always seven in all conditions and each layer has same thickness. The direction of welding and welding pass sequence are changed:

(i) One-directional continuous welding (directional): welding procedure is continuously performed from the first pass to the final pass at the same welding direction. Next welding pass begins just after finishing the last weld pass.

(ii) Turning-back continuous welding (turning-back): next welding pass is deposited by turning-back the weld torch without arc stopping. Weld metal is continuously melted by changing weld pass direction in order. This method is sometimes applied to actual steel framed structures by a registered welder in due course.

(iii) Controlled intermittent welding (controlled): weld pass is cooled down until the interpass temperature, where JASS 6 recommends as a measured position, at a point of 10 mm apart from the edge of V-shaped groove at the center along weld line on the flange upper surface, becomes less than 350 °C. Welding is continuously performed when interpass temperature does not reach 350 °C. Interpass temperature is controlled after sixth and seventh welding passes in this analysis.

The weaving process is simulated as a straight movement of the equivalent heat input. Longitudinal weld speed is set to be constant at 5 mm/s. Heat source from the weld torch is simulated by the double-ellipsoid model [22–25]. New element of the weld deposition is gradually added when the heat source is arriving at the position. Each heat input \( Q \) is determined by adjusting the boundary of melting zone to correspond with that of weld material. Comparison of heat input \( Q \) in each depositing type of multi-pass welded joints is shown in Fig. 10. The value of heat input \( Q \) is calculated from the relation between the average temperature increase and the volume of the weld joint when all boundary of the simulating model is assumed to be insulated under the actual heat input. Uniform temperature is obtained as the average temperature increase after cooling process is finished at the insulated condition, as shown in the following equation.

\[
Q = \left( C_p W \Delta T_{av} \right) / L
\]  

Here, \( C_p \) is specific heat, \( W \), weight of the specimen, \( \Delta T_{av} \), average temperature increase at insulated boundary, and \( L \) is weld length. Fig. 10 shows a comparison of heat input dependant on the welding pass sequence. Heat input at three layers are pigeonholed in the figure: the first pass (first), fourth pass which is located near the center of the thickness (mid), and the final welding pass (last). Heat input increases

| Type          | Layers | Passes | Weld pass sequence         |
|---------------|--------|--------|----------------------------|
| Directional   | 7      | 7      |                            |
| Turning-back  | 7      | 7      |                            |
| Controlled    | 7      | 7      |                            |

Table 1
Chemical composition of material used (mass%)

| C   | Si  | Mn  | Ni  | Cr  | Mo  | V   |
|-----|-----|-----|-----|-----|-----|-----|
| 0.17| 0.33| 1.37| 0.77| 0.66| 0.008| 0.002|

Table 2
Parameters of welding pass sequence
as weld deposition proceeds without reference to welding pass sequences. Controlled intermittent welding type of interpass temperature has a higher heat input at the final pass than that of other continuous pass sequences. This is because the specimen is totally cooled during waiting for next welding pass and a lot of heat needs to deposit in the controlled type. These tendency are the same as the experimental results of fabricating actual beam-to-column structures. Non-linear thermal stress analysis is done by using the temperature and microstructure distribution at each time as a thermal load with the mechanical properties of each microstructural phase. Residual stress is obtained as a result of thermal stress history that all the temperature in the welded joint cooled down until room temperature. Details of the heat conduction and thermal elastic-plastic analyses method are described in the previous references by authors [26–29].

3.6. Temperature histories during multi-pass welding

The simulated history of the interpass temperature at the recommended measuring point in JASS 6 is shown in Fig. 11. Interpass temperature is kept lower than 350 °C in controlled intermittent type specimen, but first five layers are continuously welded even though the interpass temperature is controlled. In other two types, directional type and turning-back type, welding proceeds continuously from start to finish. As a result, interpass temperature goes on rising as in Fig. 11. Turning-back continuous welding is often adopted in Japan by using flux tab at the end of the weld bead. Some welder actually uses the turning-back welding method in the beam-to-column connections for saving work time, and there is little restriction for this welding method in any present standard or specification because the turning-back operation does not affect the interpass temperature defined in JASS 6. The interpass temperature histories in JASS 6 point, near the center of the welded joint, of one-directional type and turning-back type are very similar, though the temperature histories near weld edge are completely different. These results of temperature histories show that the simplified beam-to-column welded joint in this study can validly simulate multi-pass welding heat cycles.

4. Approach to predicting and controlling mechanical properties by numerical simulation

In order to clarify the effect of welding heat cycles on phase distribution and mechanical properties of welded joints, newly developed three-dimensional heat conduction analysis considering phase transformation effect is performed. Phase transformation is simulated by using modeled CCT diagram as an input data. And the mechanical properties of welded joints are evaluated in terms of microstructural phase proportion and Vickers hardness estimated by using results of numerical analysis.

4.1. Effect of welding pass deposition on microstructure in welded joints

An example of the distribution of bainitic phase proportion near the weld material in turning-back continuous welding type and controlled intermittent type is shown in Fig. 12. The distribution of the fraction of the bainite phase in the cross-section of the center along the weld length is shown as an example of the results of numerical analysis. Phase proportion of bainite by operating the turning-back type distributes about 70–80 %, whereas that of controlled type shows more than 90%. It is evident that the fraction of the bainite phase in controlled intermittent type specimen are higher than those of continuous one-directional type and turning-back types specimens. This surely indicates that mechanical properties of multi-pass welded joints are affected by welding heat cycles.
4.2. Effect of welding pass deposition on Vickers hardness in weld metal

Comparison of Vickers hardness in the weld material between three types is shown in Fig. 13. Three cross-sections, A–C along welding direction are selected for the evaluation. The sections A and C are positioned 10 mm apart from the end of the weld bead, and the section B is located at the center of the weld length. Vickers hardness in the vicinity of the first layer and the finishing layer are shown separately. First layer side is attributed between first and second welding passes in the center of the weld material, aF, bF, and cF, and the last layer side is between sixth and seventh passes, aL, bL, and cL. The hardness of the weld metal rises when the interpass temperature is controlled as recommended in JASS 6 regardless of the location along welding direction than the other continuous depositing sequences. Hardness distribution along welding direction is not all that changed in a welding type. The effect of turning-back at the weld edge does not always affect the increase of hardness. In order to characterize the effect of welding heat cycles on Vickers hardness of the weld material, the hardness in the vicinity of the finishing layer is paid attention in the discussion. As for the weld metal at the finishing layer side, the cooling rate mainly controls the microstructural phase and Vickers hardness. Therefore the parameter $t_{85}$, the elapsed cooling time from 800 to 500 °C, is easily applied to evaluate the cooling condition of the weld metal. The distributions of the elapsed cooling time $t_{85}$ along welding direction in three depositing types are shown in Fig. 14. The cooling time $t_{85}$ in case of controlled intermittent type becomes shorter than continuous one-directional type or turning-back type due to its interval during welding. Cooling rate becomes larger in case of the controlled type. This is the reason why Vickers hardness in weld metal is higher by controlling interpass temperature in fabricating a multi-pass welded joint. Greater elapsed cooling time is generally needed near the edge, where the weld metal rises when the interpass temperature is controlled as recommended in JASS 6 regardless of the location along welding direction than the other continuous depositing sequences. Hardness distribution along welding direction is not all that changed in a welding type. The effect of turning-back at the weld edge does not always affect the increase of hardness. In order to characterize the effect of welding heat cycles on Vickers hardness of the weld material, the hardness in the vicinity of the finishing layer is paid attention in the discussion. As for the weld metal at the finishing layer side, the cooling rate mainly controls the microstructural phase and Vickers hardness. Therefore the parameter $t_{85}$, the elapsed cooling time from 800 to 500 °C, is easily applied to evaluate the cooling condition of the weld metal. The distributions of the elapsed cooling time $t_{85}$ along welding direction in three depositing types are shown in Fig. 14. The cooling time $t_{85}$ in case of controlled intermittent type becomes shorter than continuous one-directional type or turning-back type due to its interval during welding. Cooling rate becomes larger in case of the controlled type. This is the reason why Vickers hardness in weld metal is higher by controlling interpass temperature in fabricating a multi-pass welded joint. Greater elapsed cooling time is generally needed near the edge, where
weld torch is continuously turned back because the double heat input is given at the same position. The distribution along the weld line should show this tendency; left side of the turning-back welding and right side of controlled type. Cooling rate at the edge of weld material in a single-pass welded joint is, however, shorter than the center of weld material. Hardness distribution along weld line thus becomes almost constant as the result of both effects. Relation between Vickers hardness and the elapsed cooling time \( t_{\text{el}} \) in the weld metal at the finishing layer side is shown in Fig. 15. They have a strong correlation and Vickers hardness rises as the cooling rate of the weld metal becomes larger by controlling interpass temperature according to JASS 6. This is one of the effects of the interpass temperature control by JASS 6 for assuring the performance of welded joints. Interpass temperature control or lower heat input welding is effective to assure the integrity of welded beam-to-column connections of steel framed structures. Prediction of mechanical properties of welded joints is possible by simulating elapsed cooling time of welding heat cycles and using the relation to hardness. Weld material near the first layer side receives multiple weld heat cycles and it is difficult to directly apply to the CCT diagram in order to predict the proportion of microstructure. The results in Fig. 13, however, show that it has the same tendency between the first pass and the finishing pass-sides.

4.3. Effect of welding pass deposition on Vickers hardness in heat-affected zone

The effect of welding heat cycles on the width of and the hardness magnitude in the heat-affected zone is discussed. Fig. 16 shows the comparison of Vickers hardness distribution near the heat-affected zone in the diaphragm side. First layer side is attributed in the diaphragm on
the elongation line from the boundary of first and second welding passes, and the last layer side is from sixth and seventh passes. Three cross-sections, A–C along welding direction are used, the sections A and C are positioned 10 mm apart from the end of the weld bead, and the section B is located at the center of the weld bead. The magnitude and width of the heat-affected zone is determined by the heat cycles due to welding in base metal, and interpass temperature has some effect on the heat-affected zone. Hardening range by welding heat cycles is assumed as the heat-affected zone. Vickers hardness at the first layer side in one-directional welding and turning-back welding are different in the heat-affected zone though both are continuously welded. The heat-affected zone at the first layer side by turning-back welding is wider than that by one-directional welding, though the width of the heat-affected zone at the finishing pass-side is nearly the same. Effect of turning-back operation on the temperature distribution on the cross-section C near the heat-affected zone at the first layer side of the turning-back side is shown in Fig. 17. Temperature arriving at the first weld pass has the same distribution, then the second weld pass causes the different temperature distribution. The heat-affected zone by the turning-back welding is reheated by the second pass before cooling down and the width of the heat-affected zone becomes larger. Both of one-directional and turning-back types are continuous welding, and the heat input and the interpass temperature by JASS 6 are almost the same, as shown in Figs. 10 and 11. The simplified method such as JASS 6 is not always applied to the evaluation of the welding heat cycles, and mechanical properties due to different temperature histories. Comparison between continuous turning-back welding and controlled welding type shows that the distribution of Vickers hardness depends on the difference of welding heat cycle. Effect of the interpass temperature control on the maximum temperature on the cross-section B near the heat-affected zone at the final depositing layer side of the center of the weld length is shown in Fig. 18. The region, where the maximum temperature exceeds 800 °C in the turning-back welding is larger than that of controlled type, therefore the magnitude and the width of the heat-affected zone near the final weld pass-side becomes different though that near the first pass is almost the same. Interpass temperature is controlled at the sixth and seventh welding pass, and the difference of the hardness does not cause at the first pass-side but the last pass region.

4.4. Prospect of strength design by numerical simulation

Mechanical properties of a welded joint could be predicted by using the newly developed numerical analysis method presented in this paper. Appropriate control of welding conditions such as interpass temperature and heat input is very important to assure the integrity of welded joints. Simplified evaluation method such as JASS 6 should be determined by considering the effect of multi-pass welding heat cycles, as discussed in this paper. Residual stress and distortion are also important for assuring joint integrity. They naturally distribute in the welded joint, but there is little influence of welding conditions on the residual stress distribution except in the weld metal [30–33]. Fig. 19 shows an example of welding distortion and residual stress
distribution of Mises’s equivalent stress in the actual beam-to-column structure. Welding conditions affect the proportion of microstructure in the weld metal and the heat-affected zone, but these differences do not influence whole residual stress and distortion distributions. Control of mechanical properties of a welded joint is important and numerical simulation is much useful to predict them. Further study on optimizing input data of the numerical simulation dependant on microstructural phase enables to obtain more precise results in the future. Strength design of welded structures by numerical simulation enables the construction of virtual factory. In addition, preventing weld defect is surely much important and essential for assuring the joint performance.

5. Summary

Numerical simulation method of coupling analysis of temperature, microstructure, and stress–strain fields has been developed in order to predict and control mechanical properties of welded joints, and the effects of heat input and interpass temperature at multi-pass welded joint of beam-to-column connections on the strength and fracture are investigated. Tensile test, Charpy impact test, and three-point bending CTOD test are performed by using welded joint specimen fabricated with various welding conditions show that there exists a welding condition which decreases joint performance. Three-dimensional thermal elastic–plastic finite-element analysis is developed and performed by using the moving heat source and with phase transformation effect in order to evaluate the proportion of microstructure, distribution of hardness and strength. The results are shown that controlling heat input and interpass temperature is much important to assure the quality of welded joints in beam-to-column connections of steel framed structures, and that mechanical properties of the weld metal and the heat-affected zone can be predicted and controlled by using numerical simulation.

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