Study on Relationship between Material Vickers Hardness and Yield Stress of A508 Nuclear Material

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Abstract. It is difficult to directly obtain the mechanical properties of local materials of actual engineering structure (such as welded joints) by traditional mechanical test. Indentation test and ABAQUS finite element test were used in this paper, the relativity between Vickers hardness and yield stress of nuclear material A508 were studied, and a new method of using material surface Vickers hardness to acquire material properties was established. It can be used in the welded lines of nuclear dissimilar metal welded joints to obtain material parameters of mechanical property uneven zone of welded joints, and this new method was supported for complex engineering structure material mechanical parameters.

1. Introduction

Structural integrity analysis is one of the important guarantee for mechanical structure safety service, accurate material mechanics parameters is important basic data for practical engineering structural integrity evaluation[1,2]. However, the complexity of actual engineering structure processing technology, such as welded joints, it is exactly difficult to acquire mechanical properties of structural materials in vulnerable failure zones[3]. It is considered that acquiring material surface hardness is relatively easy, thus, it is a simple and feasible method to use surface hardness to calculate material mechanical properties of welded joints. Many scholars at home and abroad have carried out some preliminary studies.

J T Busby et al. took the micro hardness test of austenitic stainless steel and ferrite, and established the relationship between material hardness and yield stress[4]. M Tiryakioğlu and J S Robinson took axial tensile test and hardness test of plate 7010 alloy and straight forging 7010 alloy respectively. Finally, the empirical formula between material hardness and tensile strength was fitted out[5]. A Clausner et al. studied material yield stress by nano indentation experiment, they used two extended ECM models to simulate the indentation test and its data by finite element numerical simulation, finally, the displacement-load curve of indentation was fitted[6]. A Wagih et al. also took nano indentation experiment of Al-Al₂O₃ nano-synthetic material, and the 2D FEM numerical simulation was used to simulate the experiment process. Finally, two experiment results were compared and analyzed, and it was found out that the Young's modulus, yield stress, and hardness of synthetic materials are all higher than pure aluminium material[7]. Chen Bingchuan et al. took physical experiments of many nuclear materials, meanwhile, many relationship between hardness and yield stress of these nuclear materials were obtained and then the mathematical model of material yield stress and hardness were fitted[8]. Nie Zhishui et al. took the fatigue tensile test and indentation test of stainless steel, and the relationship between stretch deformation and cold working was found out[9]. Shen Baoluo et al. used indentation test method to inspect the product quality throughout the whole
production process, and the mathematical model of material yield stress and hardness was established, and its quite simple[10].

In this paper, Section II presents the theoretical basis of Vickers indentation test and numerical simulation were described in details. In Section III, the results was compared between Vickers hardness test and numerical simulation based on ABAQUS. Finally, Section IV presents concluding remarks.

2. Experiments Procedure

Hardness test was completed by HV-1000Z+ZZD digital micro Vickers hardness tester, the test material was from dissimilar metal welded joints in primary circuit of nuclear power plant, and the whole experiment was conducted at room temperature. This dissimilar metal welded joints were consisted of base metal: Low alloy steel(A508), stainless steel(316L), and the welded metal and surfacing layer are both nickle based alloy(152), the cladding is 304 stainless steel. The research subjects is A508 base metal, The sample and its diagram is shown in Figure 1. and Figure 2. Sample welding process is Gas Tungsten Arc Weld(GTAW), the chemical analysis results are shown in Table 1.

![Figure 1. Sample of nuclear dissimilar welded joints](image1)

![Figure 2. Sample of nuclear dissimilar welded joints diagram](image2)

| Table 1. Sample chemistry analysis(ASTM A751-2001) |
|-----------------------------------------------|
| **Element** | C  | Si | Mn | P  | S   | Cr  | Ni | Mo | Cu | Co |
| Welded line chemistry | 0.026 | 0.10 | 0.75 | 0.005 | 0.0020 | 29.49 | Margin | 0.05 | 0.06 | 0.02 |
| Nickel based isolation layer chemistry | 0.026 | 0.11 | 0.86 | 0.004 | 0.003 | 29.02 | Margin | 0.02 | 0.01 | 0.01 |
| **Element** | V  | Al | Nb+Ta | N  | Ti  | W  | Fe  | B  | Zr  |
| Welded line chemistry | 0.05 | 0.11 | 0.69 | 0.024 | 0.20 | 0.05 | 9.27 | 0.0005 | 0.01 |
| Nickel based isolation layer chemistry | 0.01 | 0.10 | 0.69 | 0.0072 | 0.22 | 0.02 | 10.11 | 0.0003 | 0.01 |

Vickers hardness test was taken in this paper, the experiment process and methods were according to GB/T4340.1-1999[11]. In this experiment, YMPZ-1 automatic polishing machine for metallographic specimen was used, distance of two indentations spacing is 100µm. It is automatically loading and unloading during the experiment that Indenter load is from 0.49N to 9.8N and holding time is 10-15s, there are three tests under the same force. The experiment principles of Vickers hardness are shown in Figure 3, the indenter is a diamond which has a regular quadrangular pyramid angle of 136° and 2 mm×2 mm geometric dimensions, The average values of indentation diagonal lines were calculated by Equation (1), and then the Vickers hardness value of the material were obtained by Equation (2), the indentation depth were formulated by Equation (3). The calculating
formula of Vickers hardness: [12,13]

![Figure 3. Schematic of hardness test](image)

\[ d = \frac{d_1 + d_2}{2} \]  \hspace{1cm} (1)

\[ HV = 0.102 \frac{F}{S} = 0.102 \frac{2F \sin \alpha / 2}{d^2} = 0.1891 \frac{F}{d^2} \]  \hspace{1cm} (2)

\[ h = \frac{d}{2 \tan(\alpha / 2)} \]  \hspace{1cm} (3)

Where HV is Vickers hardness value whose unit is N/mm², \( F \) is the test load, unit is N, which inflicted on the sample by indenter, S is the indentation area after the indenter unloaded whose unit is mm² and \( d \) is the average value of the indentation diagonal whose unit is mm. \( h \) is indentation depth. The Ramberg-Osgood relationship was consisted of yield stress \( \sigma_0 \), offset coefficient \( \alpha \), and hardening index \( n \), in order to simplify the analysis process, it was assumed that the material offset coefficient \( \alpha \) equals one, and the relationship between hardening index and yield stress were shown as Equation (4), where \( k \) is 0.163[14].

\[ n = 1/(k \cdot \ln(1390/\sigma_0)) \]  \hspace{1cm} (4)

3. Numerical Simulation Test

Sub-model technique was used for the important part of whole FEM model, mesh was used on the overall model and sub-model. The type of C3D8R mesh was used on the global model. In order to the accuracy of analysis results, grid refinement was used on the indenter and key points which contact with samples, indenter was taken as rigid, and the element of global model is 80190 in total, sub-model is 65530, the mesh model was shown in Figure 4.

![Figure 4. Finite element mesh model](image)

The indenter load is 9.8N, holding time is 15s, the boundary condition is set to full constrain on the lower surface of experiment block, meanwhile, the DOF of movement is only allowed in Y direction.

4. Results and discussions

Diagonal dimensions of indentation were acquired by numerical simulation under different pressure, as show in Table 2, the diagonal dimensions of indentation were in good agreement with Vickers hardness test, when yield stress is 460MPa and indenter load is 9.8N, it can also be found in Fig.5 and
So as to validate the reliability of analysis results between Vickers hardness test and Finite element analysis, six indenter loads, 0.49N, 0.98N, 1.96N, 2.94N, 4.9N and 9.8N, were used to take the hardness test and finite element simulation analysis.

Table 2. Indentation dimension of numerical simulation under different yield stress

| Yield Stress $\sigma_0$/ MPa | 420 | 430 | 440 | 450 | 460 | 470 |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Indentation Dimension $d$/$\mu$m | 100.1 | 98.3 | 97.2 | 96.0 | 94.7 | 93.4 |

4.1 Hardness Experiment Results

Three tests were taken under different loads of 0.49N, 0.98N, 1.96N, 2.94N, 4.9N, 9.8N, indentation images are as shown in Figure 5. It is obvious that as the indenter load increased, the indentation area increased as well.

Table 3. Indentation experiment results of A508 base metal under different loads

| $F$/$N$ | $d_1$/$\mu$m | $d_2$/$\mu$m | $d$/$\mu$m | $h$/$\mu$m | $H_v$ |
|---------|--------------|--------------|-------------|------------|-------|
| 0.49    | 19.89        | 18.76        | 18.91       | 20.91      | 19.91 | 21.06 | 20.91 |
| 0.98    | 29.0         | 29.26        | 28.47       | 28.44      | 29.51 | 28.71 | 28.88 | 5.83 | 217.34 |
| 1.96    | 42.57        | 41.50        | 40.44       | 41.59      | 41.32 | 39.98 | 41.20 | 8.32 | 212.29 |
| 2.49    | 51.08        | 51.88        | 51.08       | 53.12      | 51.25 | 51.78 | 47.56 | 9.61 | 209.26 |
| 4.9     | 67.84        | 67.31        | 67.31       | 67.88      | 67.88 | 67.61 | 67.6 | 13.66 | 202.94 |
| 9.8     | 101.63       | 96.3         | 95.78       | 100.61     | 97.13 | 96.59 | 98.01 | 19.8 | 199.36 |

The experiment data in details are as shown in Table 3, it could be found that as indenter loads increases, the indentation diagonal dimension increases, but hardness values are constant. Thus, it can be certain that material Vickers hardness is independent of the indenter pressure, it also fit to the experiment standards. The hardness value of A508 is around 210.2, which due to surface is not polish enough and the measurement of diagonal is not accurate enough etc.

4.2 Numerical Simulation Test Results

Indentation cloud map was obtained by ABAQUS finite element numerical simulation, as shown in Fig.6.

![Figure 6](image-url)
Finite element method ABAQUS was used to simulate the indentation experiment process, the indenter load is 9.8N. In order to better contact with the experimental materials to obtain the best indentation effect, the holding time is 15s, as shown in Figure 6, as the experiment indenter load increase, the indentation dimension is increase, it is also consistent with the experiment results that indenter load is proportional to indentation dimensions.

Numerical simulation test was taken when the yield stress is 460MPa, the experiment load is 9.8N, a moving degree of freedom is in Y direction and several indenter loads were set to compute, thus, the indentation results of A508 based on numerical simulation are as shown in Table 4.

| F/ N | d/ μm | h/ μm | Hv   |
|------|-------|-------|------|
| 0.49 | 11.89 | 2.40  | 231.33 |
| 0.98 | 31.11 | 6.28  | 220.74 |
| 1.96 | 41.73 | 8.43  | 212.84 |
| 2.94 | 51.62 | 10.43 | 201.92 |
| 4.9  | 67.81 | 13.70 | 201.51 |
| 9.8  | 99.37 | 20.06 | 187.68 |

The relationship between material surface hardness and indentation shape and dimension can be acquired by hardness test, meanwhile, the relationship between yield stress and indentation shape and dimensions can also be acquired by yield stress the finite element numerical simulation. Above all, the relationship between surface hardness and yield stress can be obtained by indentation which was obtained from hardness experiment and numerical simulation.

4.3 Validation and analysis between Vickers hardness experiment and numerical simulation test results

When material yield stress, which was set to the numerical simulation model, is 460MPa. Results of Vickers hardness physical experiments and numerical simulation test were fitted as shown in Figure 7. It can be found that the indentation diagonal dimension is proportional to indenter loads, furthermore, the two results are fit well, it is feasible that the method to acquire material yield stress by Vickers hardness experiment and finite element simulation analysis.
Figure 7. Diagonal length of indentation of hardness test and numeral simulation

5. Conclusions

Based on the theoretical analysis and actual situation of nuclear power plants, methods were used between numerical simulation and indentation experiment analysis, meanwhile, the basic mechanic properties of welded joints in material mechanic properties uneven zone.

(1) Basic mechanic parameters of numerical simulation are yield stress and strain hardening index, the basic mechanic parameters of hardness experiment is hardness value (HV), the relationship between material hardness and yield stress can be concluded by comparing the shape and size of two indentations;

(2) Throughout the whole Vickers hardness experiment, as the indenter loads increased, the material surface indentation depth and diagonal dimension increased, but the material hardness values are constant;

(3) A method was proposed that material surface hardness was used to acquire mechanical yield stress and other parameters, and the basic material mechanic parameters in mechanical properties uneven zone of welded joints can be roughly obtained.

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