

ESTIMATION OF THE EFFECT OF RESIDUAL STRESS ON 304 STAINLESS STEEL BASED ON WECHSLER HARDNESS TEST

Muhammad Zubair Sheikh¹, Muhammad Waqar Nasir², Rehmat Bashir³, Ali Soban⁴^{1,2,*3,4}Department of Mechanical engineering, University of Engineering and Technology, Lahore 54890, Pakistan³rehmatbashir@uet.edu.pkDOI: <https://doi.org/10.5281/zenodo.22006077>**Keywords**

residual stresses; Wechsler hardness test; 304 Stainless Steel

Article History

Received: 02 April 2026

Accepted: 12 May 2026

Published: 31 May 2026

Copyright @Author

Corresponding Author: *

Rehmat Bashir

Abstract

This study applies the indentation strain method, using a high-magnification microscope to examine the indentations created by the Wechsler hardness test. The goal is to determine how residual stress affects hardness measurements in metal materials. Specifically, this research uses a nuclear-grade 304 stainless steel sample as the test subject. By combining mechanical experiments and finite element simulations, the study investigates how tensile residual stress in metal materials impacts the results of hardness tests. The results show that when the residual stress is less than the yield limit of the material, the hardness value of the material decreases with the increase of the residual stress and vice versa. From the experimentation and simulations, it is concluded, with the increase of residual stress, the diagonal length difference of the indentation tends to increase, which is also consistent with the theoretical inference.

INTRODUCTION

There are many welded joints by dissimilar metals in the safety end of nuclear power which are affected by the service water environment, material inhomogeneity and welding residual stress and are prone to stress corrosion cracking (SCC) phenomenon [1]. The residual stress generated by welding sometimes reaches or even exceeds the yield stress of the material which has a great impact on the mechanical properties of the welded structural material [2]. Moreover, the working load at the safety end of the nuclear power plant is relatively small and the welding residual stress becomes the main driving load of SCC crack propagation. Therefore, how to obtain the residual stress distribution of metal materials has been one of the hot issues in academia for a long time.

At present, the general residual stress distribution test methods can be roughly divided into destructive test and non-destructive test.

Mathar [3] proposed the drilling method in 1934, drilling a small round hole on a specimen containing residual stress, and obtaining

residual strain by calculating the distance change before and after drilling at the calibration point near the hole, and then obtaining residual stress; Soete and Vancrombugg [4] introduced strain gauges in 1950 to improve test accuracy; Rendler and Vigness [5] The method was systematized in 1966 and the drilling method has since become an easily repeatable and widely applicable residual stress measurement method; after decades of development, the American Society for Testing and Materials established the standard for residual stress on the drilling method side in 1981 (ASTM837) [6]. However, since the round holes drilled by this method are generally only a few mm, this method usually cannot measure the internal residual stress of large specimens.

In 1951, based on the drilling method, Milbradt expanded the inner diameter of the small hole and deepened the depth, and proposed a ring core method with more accurate experimental results, but this method caused greater damage to the specimen [7]. Deep hole method is a combination of drilling method and ring core

method, can go deep into the specimen to measure the residual stress of the improved method, Zhadanov and Gonchar in 1978 first used this method to measure the residual stress of steel welded structure [8]; since 1987, Beauvey, Procter, Smith and other researchers have improved this method, has developed it into a general method that can measure the residual stress of anisotropic materials [9, 10].

In 1888, Lalakoutsky used the striping method to cut a cylinder along the length to study the residual stress distribution by measuring the change of strain on the dividing line, Schafer [11] discovered in 1998 that materials produce axial stresses and bending moments during cutting along the length, Cruise and Gardner [12] In 2008, the relationship between residual stress and bending residual stress and yield stress of stainless steel section film was obtained experimentally, which improved the accuracy of residual stress on the side of the cutting method, and the cutting method is widely used for the determination of the internal residual stress of the alloy.

Whether it is the drilling method, the deep hole method or the cutting method, it will cause irreversible damage to the test component. Therefore, for some parts that are difficult to copy, expensive or cannot be damaged, scientists have also developed some methods for non-destructive testing of residual stress.

Lester and Aborn proposed in 1925 to establish the relationship between metal grain plane spacing and residual stress by using X-ray testing, and established X-ray measurement on this basis; in the sixties of last century, German scholars improved the measurement accuracy of the method through many studies, making X-ray method a widely applicable residual stress measurement method [13, 14]. Due to the limited penetration ability of X-rays to the material, only the residual stress on the shallow surface of the material can be tested, and this method is usually used to test the thin film stress on the surface of the component.

According to the working principle of the X-ray method, the researchers introduced a neutron diffractometer to measure the grain spacing inside the metal, which greatly increased the depth of stress testing, and in the past 10 years, neutron diffraction has become more and more

widely used for residual stress determination [15].

In the 70s of last century, Underwood measured the surface residual stress of the component by pressing the spherical indentation on the surface of the test component, and observing the change of interference fringes near the indentation [16], which led to the indentation strain method; because the measurement accuracy of strain gauges is higher than that of interference fringes, in recent years, researchers have greatly improved the measurement accuracy by introducing strain gauges instead of interference fringes, and in 1992 W.C. Oliver et al. perfected the theoretical basis of the indentation method through a large number of research experiments [17], making the indentation strain method a new residual stress measurement method. However, due to the limitation of strain gauge measurement accuracy, the indentation size cannot be too small, which also indirectly makes this method unable to detect a small range of residual stresses on small components or specimens.

In the 50s of last century, researchers found that when the residual stress on the surface of metal components is tensile stress, the surface hardness of the component decreases, and when the surface residual stress is compressive stress, the surface stress increases [18]. As a near-non-destructive (Quazi-non-destructive) material property testing method, Vickers hardness test is inexpensive, easy to achieve, and its test area is usually only a few hundred microns, and a small range of hardness test results on the specimen can be obtained.

The comparative relationship between Wechsler hardness and yield stress of some metal materials has been obtained experimentally [19,20,21], and the method of estimating the mechanical properties of metal materials with the help of finite element software by deriving more accurate mechanical properties of metal materials through material hardness has also been realized [22]. However, the surface hardness of welded joints is not only related to mechanical properties, but also affected by residual stress. (Compressed).

This study draws on the principle of indentation strain method, using a high magnification microscope to observe the indentation generated

by the Wechsler hardness test, aiming to establish the influence of residual stress on the hardness test of metal materials by comparing the shape of the indentation, this time will take the nuclear power 304 stainless steel sample as the object, through the combination of mechanical experiment and finite element simulation, the influence of tensile residual stress of metal materials on the hardness test of metal materials is studied. (echoing back and forth).

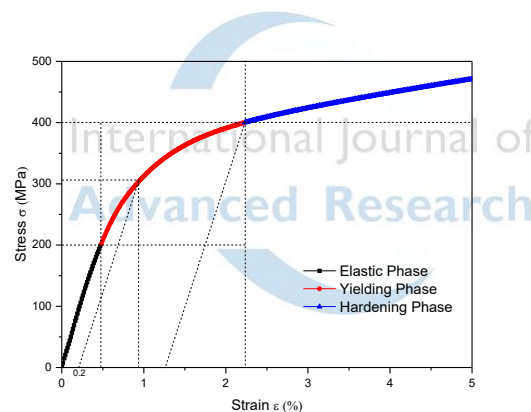
Theoretical basis

The relationship between residual stress and residual strain of materials

Welding residual stress is mainly formed by the residual strain caused by the phase change of the material and thermal expansion and contraction of the welding structure during the welding process [23], we usually think that the material

deformation of the material containing residual stress after the stress release is the residual strain, the residual strain becomes the difference between the total strain of the material and the plastic strain of the material, and the residual stress is the linear elastic relationship.

According to the magnitude of the residual stress, it can be divided into linear elastic residual stress stage and nonlinear residual stress stage. The nonlinear residual stress phase can be divided into the material yield phase and the hardening phase, as shown in Figure 1. In the linear elastic residual stress stage, there is no plastic strain in the material component, and the residual strain is the material strain, which is linear with the residual stress; when the residual stress exceeds the linear elastic stage, the material is in the yield stage or hardening stage, and the material strain and the residual stress are no longer linear.



Theoretical inference of the relationship between residual stress and material hardness

In the Vickers hardness test of the material, a diamond indenter is used to press into the test material with a certain load force, and after holding it for a period of time (15 seconds), a diamond-shaped indentation is obtained, as shown in Figure 2. By measuring the diagonal length of the diamond-shaped indentation, the material hardness value [24] is calculated. The diamond indentation has two diagonals – horizontal diagonal (h) and vertical diagonal (v), and the diagonal length d used in calculating the Vickers hardness value is the average of the two diagonal lengths. Assuming that an indentation is visible when the pressure deformation of the

specimen material under pressure reaches yield (plastic strain 0.2%), the strain value of the visual boundary of the indentation is 0.2%. The diamond indenter is a regular diamond, so the indentations generated when testing on isotropic materials are theoretically equal in length horizontally and vertically diagonally. We believe that the materials used in this study are isotropically homogeneous materials, so the stress changes generated by the hardness test process can be decomposed into independent three-dimensional stress changes. When discussing that the length of the two diagonals of the indentation is affected by the stress along the Y axis, the stress-strain change in the direction of the indentation depth (Z-axis direction) is the

same as the stress-strain relationship of the two diagonals, so the influence of this direction on the diagonal length is ignored. When the specimen contains tensile stress in the vertical direction (y direction), strain is generated, and if

the Poisson's ratio of the material is , it will produce strain in the horizontal direction (x direction). $\sigma_y \epsilon_y \lambda = 0.3$

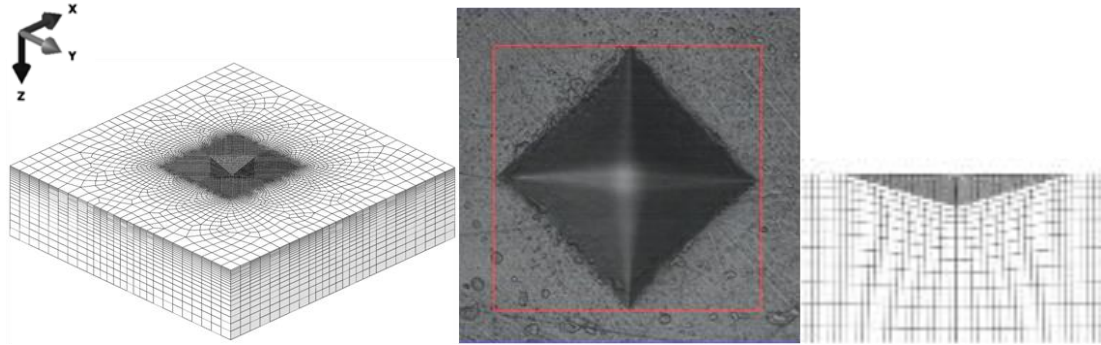


Figure 2. Schematic diagram of Vickers hardness test

$$\epsilon_x = -\lambda \cdot \epsilon_y = -0.3 \cdot \epsilon_y \quad (1)$$

According to Hooke's law, a material creates stresses in the X direction

$$\sigma_x = -\lambda \cdot \sigma_y = -0.3 \cdot \sigma_y \quad (2)$$

In this way, the length of the two diagonals is related to the diagonal length of the indenter pressing the material when the indenter presses into the material to form an indentation $d_h d_v d_0$

$$d_h = d_0 - Rh \quad (3)$$

$$d_v = d_0 - Rv \quad (4)$$

Rh, Rv is the amount of springback of the diagonal length when the indentation is formed. As an example $\sigma_y = 200\text{MPa}$, as shown in Figure 3, the diagonal length of the indentation formed by the hardness test

$$d_{h200} = d_0 - Rh_{200} \quad (5)$$

$$d_{v200} = d_0 - Rv_{200} \quad (6)$$

Therefore, the difference between the two diagonals is

$$|d_{h200} - d_{v200}| = |Rh_{200} - Rv_{200}| \quad (7)$$

From the material mechanics theorem, it can be inferred that the greater the residual stress, the greater the diagonal difference.

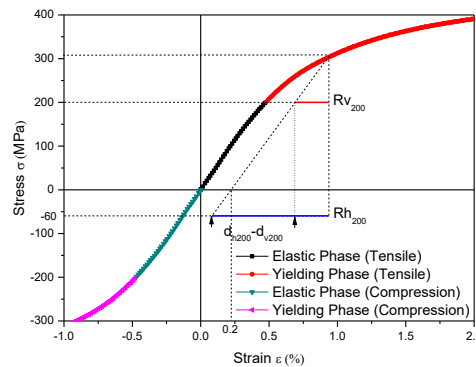


Figure 3. Schematic of biaxial rebound for 304

Experiment Procedure**Determination of specimen material parameters**

The elastic modulus of elasticity in the elastic stage was tested using the Astron material testing machine using the specimen sticker strain gauge, and then the tensile test was performed on the specimen made of the same batch of the same material, and the material mechanical property parameters and stress-strain curve of the 304

stainless steel specimen used in this experiment were obtained, as shown in Figure 4. Since the 304 stainless steel specimen used this time has no obvious yield point, the stress value that produces 0.2% plastic strain is used as the yield stress according to the industry practice. The elastic modulus of the specimen used in this experiment was 207GPa and the yield stress was 314MPa.

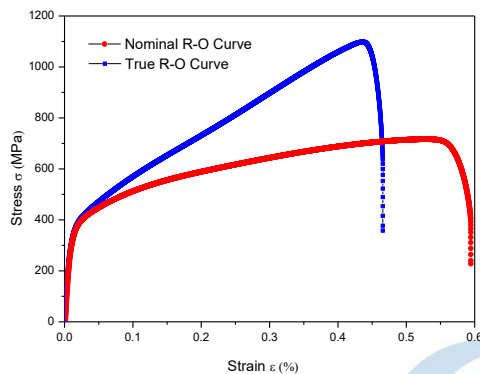


Figure 4. Nominal stress-strain curve and true

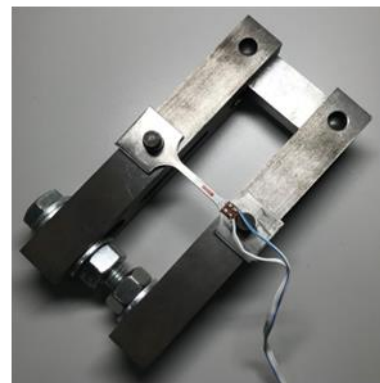


Figure 5. Residual stress device

Design of tensile stress holding device

The main purpose of this research is to explore the relationship between hardness and residual tensile stress of metal materials. Taking 304 stainless steel as the research object, the tensile stress continuous loading fixture is designed, as shown in Figure 5, so that the 304 stainless steel specimens can be subjected to Vickers hardness test while tensile stress is applied. The specimen is made of 304 stainless steel material, processed by wire cutting, and the specimen tensile test area size. $2\text{mm} \times 3\text{mm} \times 20\text{mm}$. This experimental setup simulates tensile residual stress by applying tensile loads and holding on the specimen and enables hardness testing of specimens with tensile internal stresses. The unit is loaded using the lever principle, which allows for large specimen loading with a small loading force, while the specimen is always only subjected to tensile loads due to the pin connection loading of the fixture of the device. Since the device cannot directly control the loading force during loading, a strain gauge is installed on the specimen, and the stress load of the specimen is reversed by the specimen strain value corresponding to the known stress-strain

correspondence (Figure 4). To obtain the stress-strain correspondence of the specimen, the specimen equipped with strain gauges is subjected to a stress-strain test using an Astron tensile testing machine to obtain the stress-strain curve of the specimen, as shown in Figure 4. The specimen is mounted on the internal stress loading device, and the nut on the loading rod is turned to move the two nuts away to apply a tensile load to the specimen.

Specimen hardness test with tensile internal stress

For the tensile hardness test of 304 stainless steel, the sample is loaded as tensile stress every 33MPa in the range of 0-400MPa, and the hardness test of the pattern is carried out at the same time as tensile loading, and the horizontal, vertical diagonal length, Wechsler hardness value and indentation image are obtained. Six hardness tests are performed for each stress loading value, each recording the horizontal diagonal length d_h , vertical diagonal length d_v , and hardness value H_v . The maximum and minimum hardness values in the 6 tests were

discarded, and the average values of d_h , d_v , and H_v were calculated for the remaining 4 sets of data. $|d_h - d_v|$.

Simulation calculations

Determination of material parameters

The specimen material parameters are calculated using the real stress and true strain calculated from the nominal stress and nominal strain measured experimentally, and the true stress-strain curve is calculated $\sigma_{nom} \epsilon_{nom} \sigma_{true} \epsilon_{true}$ as shown in Figure 4.

True stress:

$$\sigma_{true} = \frac{F}{A} = \frac{F}{A_0 \frac{l_0}{l}} = \sigma_{nom}(1 + \epsilon_{nom}) \quad (8)$$

Real Adaptation:

$$\epsilon_{true} = \int_{l_0}^l \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right) = \ln(1 + \epsilon_{nom}) \quad (9)$$

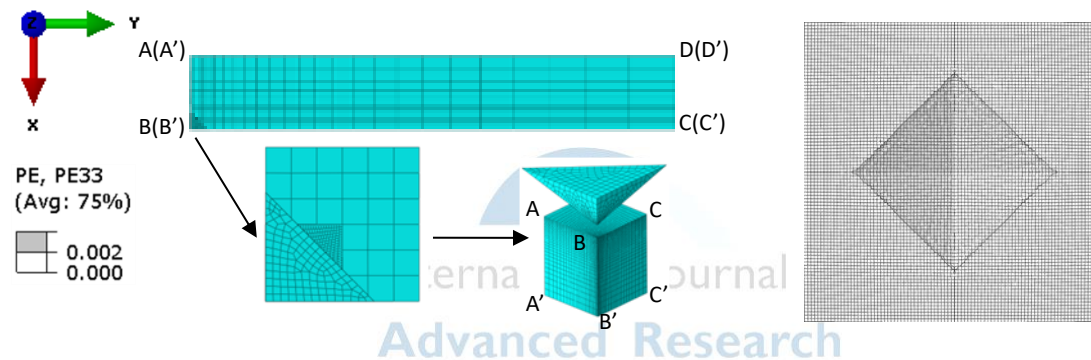


Figure 6. Schematic diagram of the finite element model of specimen and

Model Establishment

In this study, the finite element simulation software ABAQUS was used to simulate the hardness test process of the specimen. Since the hardness test indenter and indentation are symmetrical in both directions diagonally, a 1/4 finite element model is established to reduce the amount of calculation, the sample test area size is $1\text{mm} \times 1.5\text{mm} \times 10\text{mm}$, and the hardness test area is $0.25\text{mm} \times 0.25\text{mm} \times 0.3\text{mm}$ as the indentation area to refine the mesh, as shown in Figure 6.

The indenter material is made of discrete rigid body, and the hexahedron is freely meshed. The specimen material unit is selected C3D8R, the structure is meshed, and the number of elements is 27000.

4.3 Boundary Conditions and Loading

The finite element geometry model established this time is a 1/4 model, as shown in Figure 6,

so the left and lower surfaces of the model are $ABB'A'$ and $BCC'B'$ respectively. XZ and YZ symmetrical constraints are applied; in order to prevent bending, a displacement constraint in the Z direction is applied to the bottom surface $A'B'C'D'$ so that the displacement along the Z axis is always 0; the indenter is displaced in the X and Y directions and along X . The rotational constraints of the Y and Z axes allow them to move only in a straight line in the Z axis. CDD through the right end face of the specimen 'C'. The corresponding displacement load is applied to achieve tensile residual stress load every 33MPa in the range of 0-400MPa; 2.45 in the straight line along the Z axis is applied to the 1/4 indenter

N, so that the indenter downforce is 9.8N.

Results

Experimental Results

As shown in Figure 7, by comparing the hardness value of 304 stainless steel specimen under different internal stresses, it can be found that in the range of 0-300MPa, with the increase of tensile internal stress value of the specimen, the hardness of the material shows a downward trend; but as the tensile internal stress continues to increase, after exceeding 300MPa, the hardness value of the specimen increases with the increase of the tensile internal stress value. The reason for this phenomenon is that when the tensile stress gradually increases close to the yield stress of 315MPa, the material gradually yields and softens, and the hardness value of the material decreases; and when the tensile stress exceeds the yield stress, the material begins to work harden, so that the specimen material hardens and the hardness value increases, which makes the direct use of the material hardness corresponding to the residual stress of the metal

material is only suitable for the stage where the residual stress is less than the yield stress of the material.

By comparing the diagonal length d_h , d_v and difference of the indentation under different residual stresses, it is found that when the 304 stainless steel specimen is subjected to tensile residual stress, regardless of whether the specimen is in the linear elastic stage or the nonlinear stage (including yield softening segment and work hardening stage), the diagonal length d_h in the horizontal direction of the indentation is greater than the diagonal length d_v in the vertical direction. Through comparison, it is found that with the increase of the horizontal tensile stress of the specimen, the difference between the diagonal length of the indentation horizontal and the diagonal length in the vertical direction gradually increases, and the growth slows down when the tensile stress reaches near the yield stress.

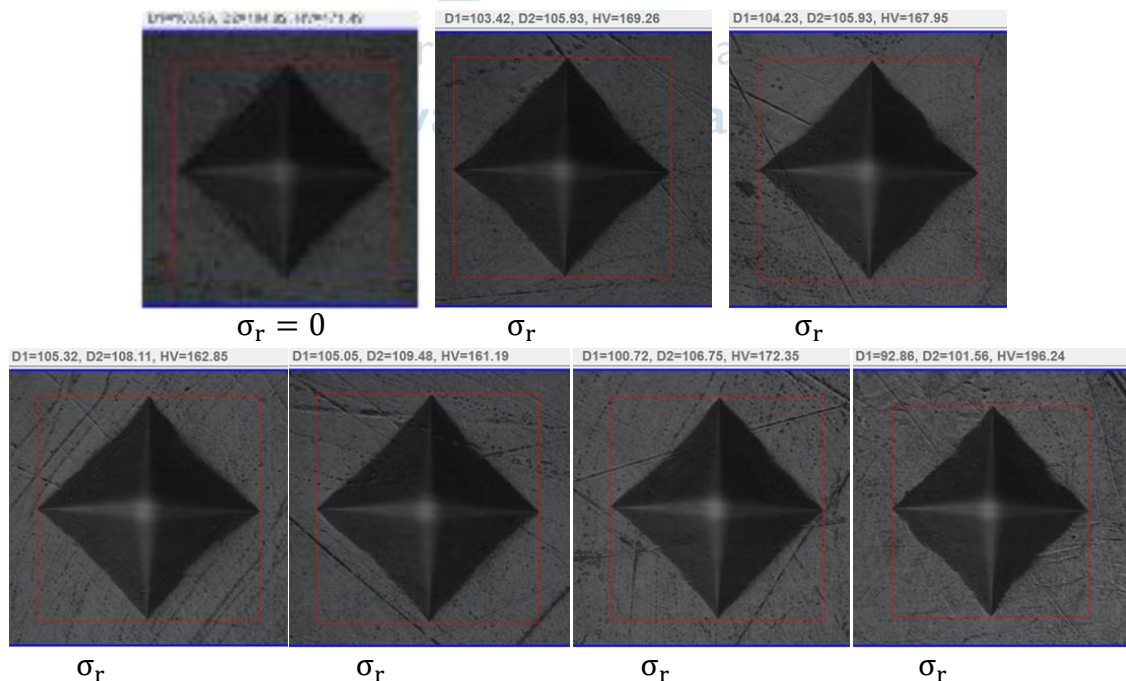


Figure 7. Vickers hardness test indentation of 304 stainless steel specimen under the influence of specific residual stress (D1, D2 are diagonal lengths along the X and Y directions, in μm ; HV is the Wechsler hardness value in kgf/mm^2)

Numerical simulation results

The finite element simulation software ABAQUS was used to simulate the Wechsler hardness test process of 304 stainless steel

specimens with residual tensile stress, and the hardness value and diagonal length difference measured by the residual stress value every 33MPa in the range of 0-400MPa were obtained.

Since the finite element software cannot directly obtain the hardness value and the diagonal length value of the indentation, this numerical simulation experiment uses the indentation depth to calculate the hardness value of the specimen, and the diagonal length is measured by observing the indentation contour plastic strain cloud.

According to the experimental principle of Vickers hardness, the formula for calculating the hardness of the material is as follows:

$$H_v = 0.102 \frac{F}{S} = 0.102 \frac{2F \sin \frac{\alpha}{2}}{d^2}$$

$$= 0.1891 \frac{F}{d^2} \quad (10)$$

Among them, H_v makes the Vickers hardness value, N/mm²; F is the loading force, the counterweight used in this study is 9.8N; S is the indentation area generated, mm²; d is the average length of the two diagonals of the indentation, mm.

D is related to the indentation depth H

$$= h \cdot \tan 68^\circ \quad (11)$$

Therefore, the material Vickers hardness H_v has

$$= \frac{0.3025 H_v}{h} \quad (12)$$

According to the numerical simulation experimental results, the tensile residual stress has an effect on the hardness value and indentation diagonal length of the 304 stainless steel specimen, as shown in Figure 8, as shown

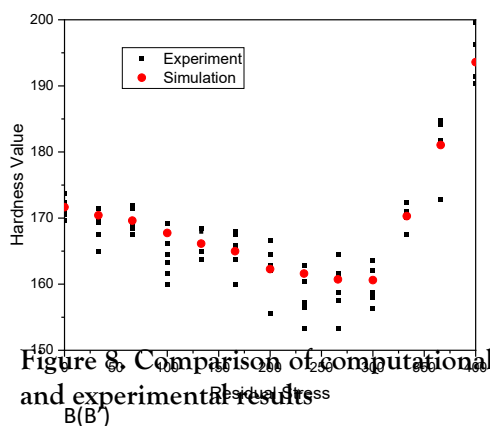


Figure 8. Comparison of computational and experimental results

Conclusions

1. The experimental and numerical simulation results show that the residual stress in 304

in the figure in the range of 0-300MPa, the hardness value of the specimen slowly decreases with the increase of the tensile residual stress value, in the range of 300-400MPa, the hardness value of the specimen increases significantly with the increase of the tensile residual stress value; as shown in Figure 9, in the range of 0-400MPa, the diagonal length difference of the indentation of the specimen increases with the increase of residual stress.

Comparison of experimental results with numerical simulation results

By comparing the hardness test and numerical simulation test results, when the 304 stainless steel specimen is subjected to the residual stress of 0-300MPa, the hardness of the specimen gradually decreases with the increase of residual stress, and the overall trend is consistent with the previous research results and the simulation results; when the residual stress of the specimen reaches 300-400MPa, the hardness of the material increases significantly with the increase of the residual stress value, and the hardness test is consistent with the trend of the simulation results. At the same time, when 304 stainless steel is subjected to 0-400MPa residual stress, the angular length of the hardness test indentation along the direction of tensile residual stress is greater than the diagonal length in the other direction, and the length difference expands with the increase of residual stress.

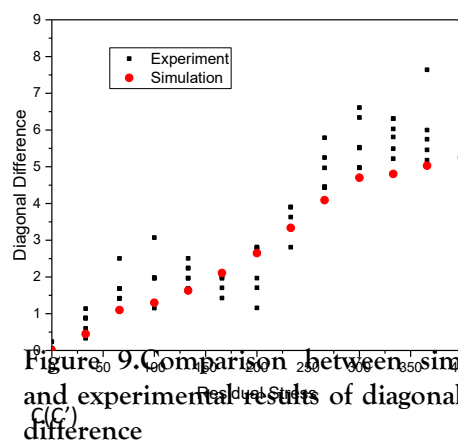


Figure 9. Comparison between simulation and experimental results of diagonal length difference

stainless steel has an impact on the hardness test results of the metal material, when the residual stress is less than the yield limit of the material,

the hardness value of the material decreases with the increase of the residual stress; when the residual stress exceeds the yield limit of the material, the hardness of the material increases significantly with the increase of the residual stress due to the influence of work hardening.

2. According to the experimental and numerical simulation results, the residual stress has an effect on the diagonal length difference of the indentation of the hardness test of 304 stainless steel specimen, and the angular length of the hardness test indentation along the direction of tensile residual stress is greater than the diagonal length in the other direction, and with the increase of residual stress, the diagonal length difference of the indentation tends to increase, which is also consistent with the theoretical inference.

3. By observing the Vickers hardness value of metal materials and the diagonal length of indentations generated by hardness test, the residual stress distribution trend in metal material samples can be inferred, and this conclusion provides a theoretical basis for testing the residual stress on the surface of metal materials by microhardness tester.

REFERENCES

- [1] Xue H, Ogawa K, Shoji T. Effect of welded mechanical heterogeneity on local stress and strain ahead of stationary and growing crack tips. *Nuclear Engineering and Design* 2009; 239(4): 628–640.
- [2] Ren Y, Paradowska A, Wang B, Eren E, Janin YJ. Residual Stress State of X65 Pipeline Girth Welds Before and After Local and Furnace Post Weld Heat Treatment. *Journal of Pressure Vessel Technology* 2017; 139(4): 041401.
- [3] Mathar J. Determination of initial stresses by measuring the deformation around drilled holes. *Trans. ASME* 1934; 56(4): 249–254.
- [4] Soete W, Vancrombrugge R. An industrial method for the determination of residual stresses. *Proc. SESA* 1950; 8(1): 17–28.
- [5] Rendler NJ, Vigness I. Hole-drilling strain-gage method of measuring residual stresses. *Experimental Mechanics* 1966; 6(12): 577–586.
- [6] ASTM. ASTM E 837-08 Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. West Conshohocken, PA: ASTM International; 2008.
- [7] Milbradt KP. Ring method determination of residual stress. PhD thesis, University of Illinois, 1950.
- [8] Zhandano IM, Gonchar AK. Determining the residual welding stresses at depth in metals. *Automatic Welding* 1978; 31: 22–24.
- [9] Beaney EM, Procter E. A critical evaluation of the centre hole technique for the measurement of residual stresses. *Strain* 1974; 10(1): 7–14.
- [10] Smith DJ, Poussard CGC, Pavier MJ. An assessment of the Sachs method for measuring residual stresses in cold worked fastener holes. *The Journal of Strain Analysis for Engineering Design* 1998; 33(4): 263–274.
- [11] Schafer BW, Peköz T. Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses. *Journal of Constructional Steel Research* 1998; 47(3): 193–210.
- [12] Cruise RB, Gardner L. Residual stress analysis of structural stainless steel sections. *Journal of Constructional Steel Research* 2008; 64(3): 352–366.
- [13] Dölle H, Hauk V. Hardening Tech. *Mitt* 1976; 31: 165–168.
- [14] X-ray Material Strength Committee of Japan Society of Materials. Standard method for X-ray stress measurement. The Society of Materials Science, Japan; 2005.
- [15] Withers PJ. Mapping residual and internal stress in materials by neutron diffraction. *Comptes Rendus Physique* 2007; 8(7-8): 806–820.
- [16] Underwood JH. Residual-stress measurement using surface displacements around an indentation. *Experimental Mechanics* 1973; 13(9): 373–380.

- [17] Oliver WC, Pharr GM. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of Materials Research* 1992; 7(6): 1564-1583.
- [18] Sines G, Carlson R. Hardness measurements for determination of residual stresses. *ASTM Bull* 1952; 180: 35-37.
- [19] Tiryakioğlu M. On the relationship between Vickers hardness and yield stress in Al-Zn-Mg-Cu Alloys. *Materials Science and Engineering: A* 2015; 633: 17-19.
- [20] Şerban VA, Codrean C, Vodă M, Chicot D, Decoopman X. Correlation between yield stress and hardness of nickel-silicon-boron-based alloys by nanoindentation. *Materials Science and Engineering: A* 2014; 605: 294-300.
- [21] Hosoda H, Yoshimi K, Inoue K, Hanada S. Effect of wet environment on hardness and yield stress of B2 Fe-Al alloys. *Materials Science and Engineering: A* 1998; 258(1-2): 135-145.
- [22] Xue H, Zhuang ZC, Cao T, Guo R, Cui YH, Gong XY. Relationship analysis between Vickers hardness and yield stress of structure material. *Journal of Xi'an University of Science and Technology* 2017; 37(2): 274-27
- [23] Hearn EJ. Contact stress, residual stress and stress concentrations. *Mechanics of Materials* 1997; 2: 381-442.
- [24] Mott BW. Micro-indentation hardness testing. London: Butterworths Scientific Publications; 1956.