DOI: 10.24425/amm.2019.129455

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# ANALYSIS AND VERIFICATION OF PHYSICAL PROPERTIES OF AN AISI 4140 STEEL BY VICKERS INDENTATION ANALYSIS ACCORDING TO THE PRESENCE OF RESIDUAL STRESSES

Residual stress has a great influence on the metal, but it is difficult to measure at small area using a general method. Residual stress calculations using the Vickers indentation can solve this problem. In this paper, a numerical simulation has been made for the residual stress measurement method of metal material deformed by high-speed impact. Then, the stress-strain curve at the high-speed deformation was confirmed through actual experiments, and the residual stresses generated thereafter were calculated by the Vickers indenter method. A Vickers indentation analysis under the same conditions was performed at the position where a residual stress of about 169.39 MPa was generated. Experiments were carried out and high speed impact was applied to the specimen to generate residual stress. The obtained results indicate that it is possible to identify residual stresses in various metals with various shapes through Vickers indentation measurements, and to use them for process and quality control.

*Keywords:* Vickers indentation, Residual stress, FEM Analysis, Material Property, Surface Treatment

## 1. Introduction

Due to the development of metal processing technology, various design and machining techniques have been studied. In particular, the demand for special processing technologies such as sheet cutting and precision heat treatment is increasing, and the problem of residual stress caused by such special processing methods is increasingly considered [1].

Residual stress is not so important for bulky materials, but it is very important to measure and verify the effects of twisting problems in processing such as sheet metal forming [2-3]. In other words, although the residual stress is an important factor affecting the physical properties of the metal depending on its aspect or degree, there is no way to directly measure the local residual stress, so a method of measuring the residual stress using the Vickers indenter is proposed. Several numerical and experimental studies on these measurement methods and verification through actual measurements were performed [4-6].

However, these previous studies mainly measured residual stresses based on tensile and deformation in the direction of the plane, and there was no consideration of the reaction force on the pressurizing direction of the indenter. In addition, the residual stress caused by external impact load directly affects the strength and durability of the material. The residual stress generated in actual collision is generated irregularly with the Hertzian force around the contact surface. This is because plastic deformation occurs with high energy shock wave [7-8].

Despite these direct and significant effects, there has been no study of the change in the physical properties of materials and the measurement of residual stresses that occur randomly by impact. Therefore, the residual stress generated by the impact load must be considered simultaneously in all three dimensions, not the two-dimensional force. In this study, an integrated analytical model by linking the Vickers indentation with a radical deformation process by collision is proposed.

For this purpose, the influence of high-speed impact on the specimen was analyzed through previous study and shown in Fig. 1 [9]. The high-speed deformation properties derived from previous studies were applied to the Johnson-Cook model and the results of the analysis and the experiment were compared. The effect of residual stress on the irregular residual stress caused by high-speed collision was applied to the Vickers indentation simulation. The high stress-strain curve was measured by impact experiment, and the residual stress of the obtained metal specimen was measured and compared.

## 2. Residual stress calculation

As in a previous study [10], the residual stress calculation using the Vickers indentation test was performed based on the

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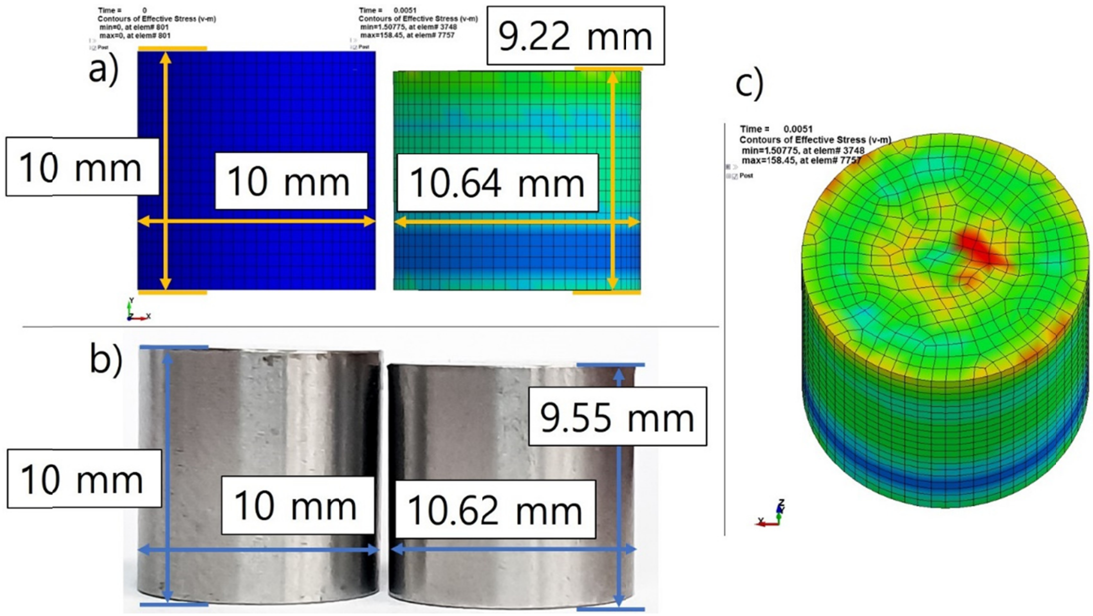


Fig. 1. Numerical (a) and experimental (b) result of high speed deformation and residual stress generation. And top surface of numerical analysis result (c)

differences in the indentation load-indentation depth curve according to the residual stress. Two different curves were obtained based on the force differences at the same depth between the two curves. These curves are shown in Fig. 2.

$$\sigma_{res} = L_{res} / A_c \tag{1}$$

$$A_c = 24.5\, h_c^2 \tag{2}$$

This difference in force can be calculated as residual stress based on the Eq. (1). In this equation, the value of $L_{res}$ is the difference in indentation load up to the same leading depth, and if this value is positive, compressive stress is generated, and a negative value is the opposite. The $A_c$ is the value for the contact area of the indentation depth of the Vickers indentation tip. Based on this equation, the difference in indentation load versus Vickers indentation depth was measured, and the residual stress was calculated.

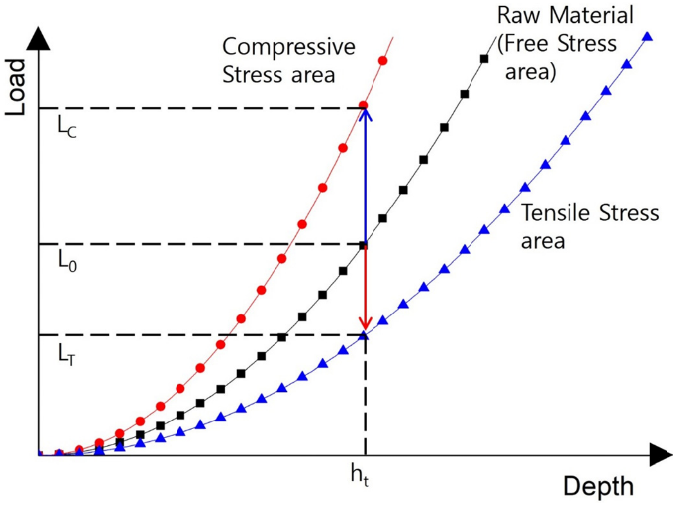


Fig. 2. Relationship between Vickers indentation depth and load

## 3. Experimental procedure

In this study, the behavior of the Vickers indenter is simulated numerically and the change in the repulsive force against the indentation displacement is verified. For comparison, numerical analysis was carried out for the untreated metal specimens and the specimens with residual stress due to the impact force.

### 3.1. Finite element method Set-up

The analysis of the residual stress measurement specimen was carried out in two steps, an impacting process, and the Vickers indentation test. The initial impact for the residual stress was set by compressing the rigid plate under the specimen in short time so that residual stress was generated, and then the Vickers indentation test was performed on the upper center point. Numerical analysis of uncompressed specimens is a reference for zero residual stress calculation. Therefore, the indentation analysis of raw material was carried out without compression analysis.

The analytical conditions of Vickers indentation were set by the general test conditions. However, to reduce the analysis time, the Vickers indenters were pressed by a depth of about 50 μm. This condition was applied to both of analysis which the specimens with impact force, or not.

### 3.2. Pre-process of finite element methods

The pre-processing was performed using the "Mechanical" software of ANSYS and numerical analysis was performed by LS-DYNA explicit code, for good convergence at large deformations, and has been analyzed using the advanced contact conditions in LS-DYNA. The specific physical properties of AISI 4140 steel specimen and the Diamond Vickers Tip are shown in Table 1 [11,12]. As the impact was applied to the metal specimen at a high speed, the behavior of the metal was analyzed with the Johnson-Cook strain-rate sensitive model that can consider the work-hardening effect due to speed. The properties of related specimens [13] are shown in Table 2 below.

TABLE 1

Mechanical Properties of AISI 4140 [10,11]
and the Diamond Vickers tip [10]

| Property | AISI 4140 | Diamond | Unit |
|---|---|---|---|
| Density | 7850 | 3363.1 | kg/m$^3$ |
| Young's Modulus | 205 | 863 | GPa |
| Yield Stress | 415 | | MPa |
| Poisson's ratio | 0.3 | 0.2 | |
| Tip feed speed | 0.8 | | mm/min |

TABLE 2

Johnson-Cook Mechanical Properties of AISI 4140 [11,12]

| Property | AISI 4140 | Unit |
|---|---|---|
| Yield Stress (A) | 415 | MPa |
| Hardening Modulus (B) | 768 | MPa |
| Strain rate dependency (C) | 0.0137 | |
| Work hardening coefficient (n) | 0.807 | |
| Thermal softening coefficient (m) | 0.2097 | |
| Melting Temperature | 1520 | °C |

Fig. 3 is the analytical model used in this study, and a quarter size partial model of the actual specimen was used to reduce the analysis time. The cross section of the 1/4-size specimen was set to proceed in the same way as that of the entire specimen. The finer mesh size set at contact surface for the reliable analysis results. Thus, the number of nodes used for the analysis was 7,215. For a more accurate calculation, the contact properties of the Vickers tip and specimen were set as the node-node and node-surface conditions at the same time.

## 4. Results and compare with experiment

A numerical analysis was performed as described above, and the results are shown in Fig. 4. From the results of the analysis, we confirmed the relationship between indentation load and the indentation depth. Because of the analytical grid shape, the results were not smooth and the values were compared using a second order polynomial trendline. The indentation load curve for the Vickers indentation depth is shown in Fig. 5. The figure shows that compressed specimens required higher loads than the raw materials used in the Vickers indentation tests. The residual stress was calculated by substituting the numerical analysis results into Eq. (1) and the value was 165.25 MPa.

For the verification of the trend, impact was applied so that a similar residual stress was generated in the actual specimen. The 10 mm height specimens were placed between the steel bars of 20 mm diameter and 1200 mm length, and a striker bar was blown to the steel bar with compressed air and the specimen was impacted at a speed of 30 m/s [14]. The amount of deformation of the specimen caused by the impact was controlled to be the same as that of the deformation value of analysis. Strain stress curves at high speed impact were measured by measuring the shock waves passing through the steel bars. The stress-strain was calculated from the following Eq. (3).

$$\sigma_s = E\left(\frac{A}{A_s}\right)\varepsilon_T, \quad \varepsilon_s = -\frac{2C_0}{L_s}\int_0^t \varepsilon_R(t)\,dt \qquad (3)$$

The $\sigma_s$ is true stress, $\varepsilon_s$ is true strain of high-speed impact test. The $A$, $A_S$ used for the calculation are diameter of test equipment and specimen. And the $\varepsilon_T$, $\varepsilon_R$ are measured strain of steel bars.

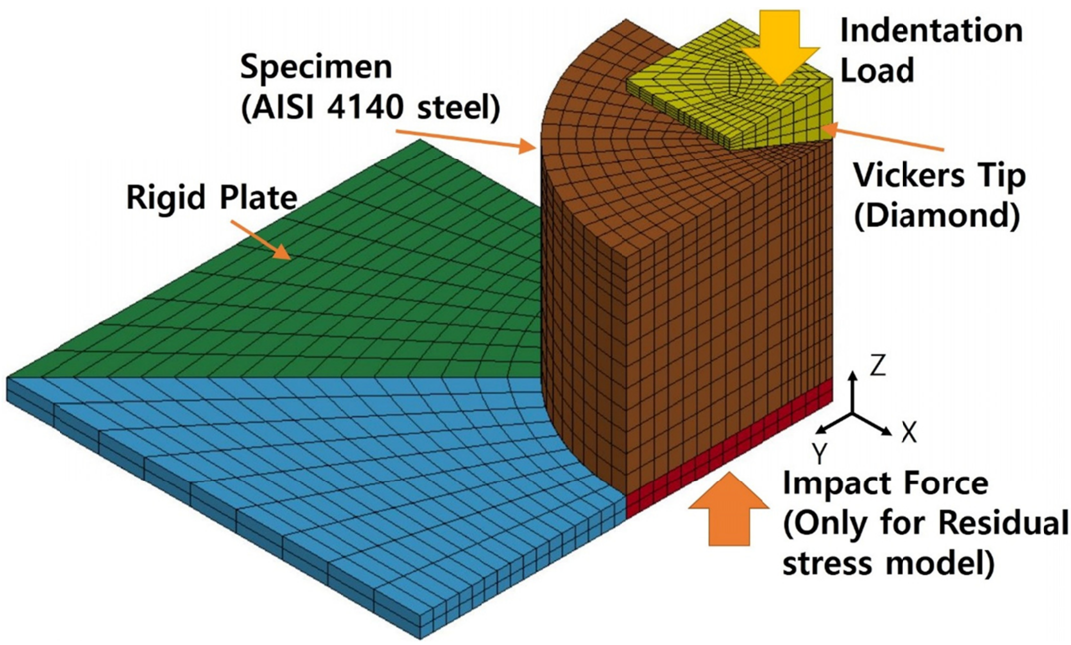


Fig. 3. Analysis model

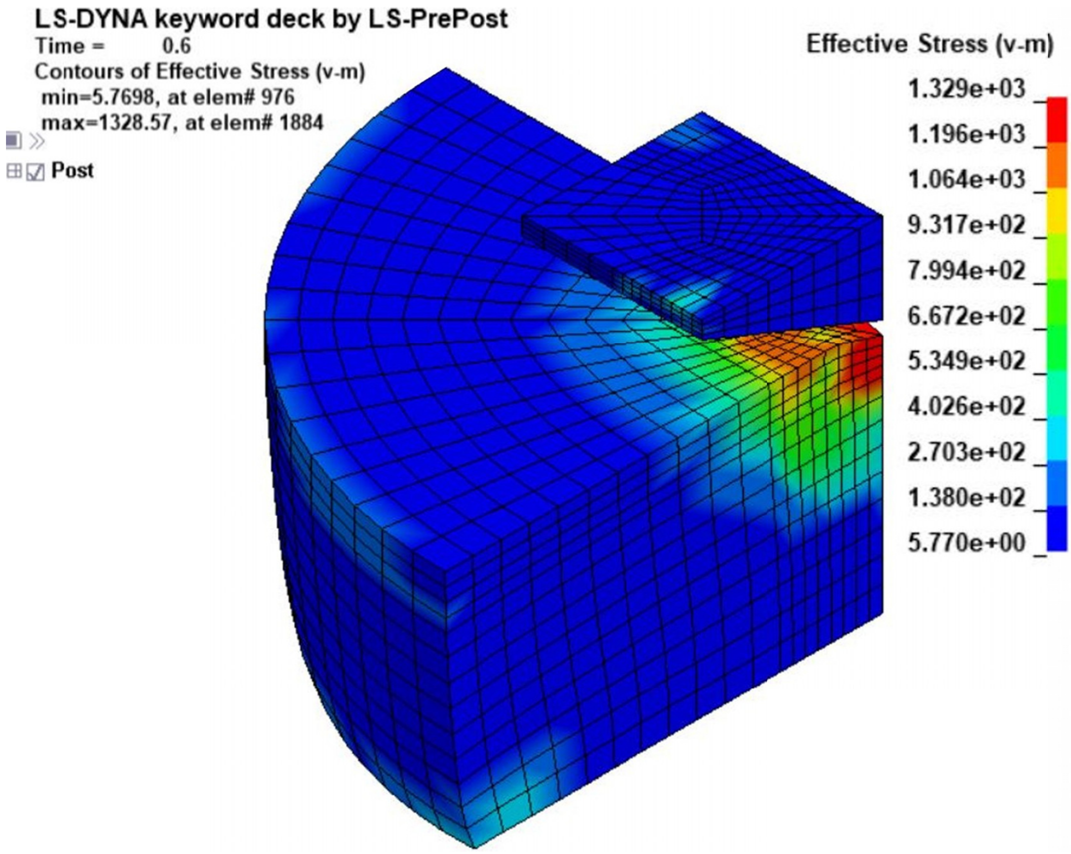


Fig. 4. Analysis result

According to the measuring device, the $C_0$ and the $L_s$ are 5000 and 10, respectively. The stress-strain curve calculated from these values is shown in Fig. 6.

When the fast deformation due to impact was measured, the modulus of elasticity did not change much, and the allowable stress increased by about 100 MPa compared with the general tensile test coefficients. Also, comparing the plastic deformation sections, the slope did not change significantly according to the impact velocity, which was confirmed by the previous studies. Based on this, it was confirmed that the reliable results were measured [15].

The residual stress was measured by the Vickers indentation test on the test specimen subjected to such a high-speed impact. An experiment was performed under the same conditions to confirm the value of the residual stress. The measured values are shown in Fig. 7. The residual stress was calculated as 150.21 MPa. The difference between the analytical results and the actual test results was about 9.1%, and the tendency is generally correct when compared with the existing reference [4]. This error is because the residual stress generated by the specimen and the residual stress due to the applied force are not constant.

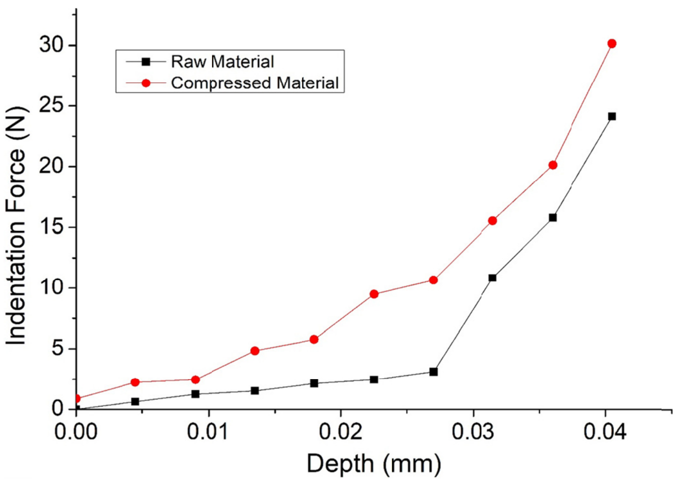


Fig. 5. Analysis result of Vickers indentation depth vs. load

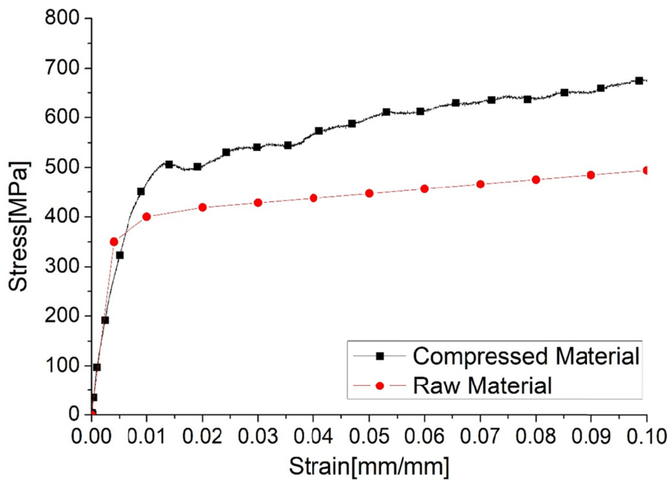


Fig. 6. Stress-Strain Curve with different deformation speed

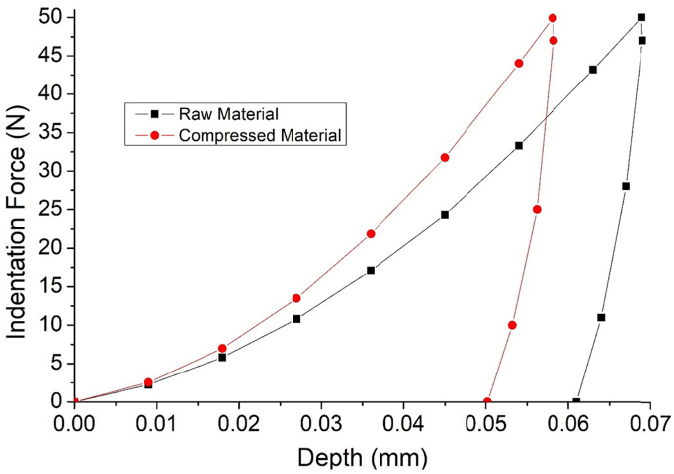


Fig. 7. Experimental result of Vickers indentation depth vs. load

### 5. Conclusions

In this paper, the impact deformation and the Vickers indentation process are numerically simulated and compared with the high-speed impact test and the Vickers indentation test. Impact analysis and Vickers indentation analysis were simulated in conjunction with FEM and residual stress values were calculated based on the analysis results. The impact test confirmed that the stress-strain curve varied at high-speed deformation, and that the yield strength increased. After that, it was confirmed that the indentation load-indentation depth curve of the Vickers indenter changed with a similar tendency as the actual test procedure with some errors, and the residual stresses generated by the impact of the indenter were calculated from this value.

The main reason for the error between the numerical analysis results and the experimental results seems to be that the reference indentation depth-indentation load curve was measured differently owing to the residual condensation generated in machining the standard raw specimen.

Further studies are necessary to confirm that the same method is applicable for residual stress measurement of brittle metals. It is difficult to measure the residual stress when metal cracks due to brittleness. The method proposed in the study can be used to calculate residual stresses in local areas. Furthermore, it may be used to measure the residual stress in areas where measurements by conventional methods are difficult to perform.

**Acknowledgments**

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea ) (No. 20165020301430).

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