521 Spring-back analysis based on microscopic measurement of deformation and material properties

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Abstract: In sheet metal forming, spring-back phenomenon is important issue and microscopic evaluation of materials is required. In this study, in order to clarify relationship between the changes of material structure or material properties and the plastic strain, analysis and experiment were performed. First, the changes of thickness distribution for mild steel sheets were measured by analyzing the cross-sectional microphotographs of material structure. And next, the relationship between Young’s modulus or hardness and the plastic strain was investigated by cyclic nano-indentation testing by which micro regional material properties can be obtained. Consequently, the distributions of grain oblateness and its changes caused by V-bending were quantitatively obtained by analyzing the microphotographs. Moreover by cyclic nano-indentation testing, hardness was decreased by increasing plastic strain. Though the quantitative evaluation of Young’s modulus was tough work and we couldn’t find peculiar tendency, stable value of it could be measured where maximum indentation load was larger than 1000 μN.

Key Words: spring-back, grain oblateness, nano-indentation test, micro-macro relationship, simulation

1. INTRODUCTION

In sheet metal forming, the product geometry errors due to the spring-back phenomenon are increasing the die compensation man-hour and the production preparation lead time. In order to reduce the product weight, the high strength steel sheet has been very rapidly replacing the mild steel sheet for automobile bodies. However, its formability and shape controllability are considerably poor, especially for the purpose of production of the strictly designed shape.

On the other hand, numerical simulation technique has progressed remarkably. Nowadays in sheet metal forming, FE simulations are used steadily. The main purpose is in advance assessment of the formability. Though the spring-backed shape can be predicted by the FE simulation, the accuracy is not enough for us to make use of it actually. Therefore further study of material modeling is necessary in order to achieve a more precise prediction.

Up to now many constitutive equations were proposed to describe deformation behavior in the forming processes. However, most of them are based on the continuum mechanics and the experimental results such as tensile and compression tests from macroscopic aspects. Therefore they can’t respond to the scattering of spring-back value caused by that of microscopic material characteristics.

In this study, we evaluated the influence of through-thickness distributions of the grain oblateness in mild steel sheet and change of Young’s modulus and hardness on material macroscopic characteristics by observing microphotographs of material structure and cyclic nano-indentation testing. We attempted to establish a link between the microscopic changes of the material properties and the macroscopic behavior such as formability and spring-back, and make a mathematical model considering micro-macro relationships.

2. ANALYSIS OF GRAIN OBLATENESS

2.1 Test piece

The test piece used in this work was rolled mild steel sheet (SPCC-SB, thickness t = 1.2mm). As shown in Figure 1, it was sectioned into two parts. One of
them was V-bended to 90 degree and the other was remained as received. And then, both of them were polished and etched in solution. Here, The dimension of test pieces was $3L \times 10 \times 1.2 \text{ mm}$ because of restriction of AFM observation.

![Figure 1 Test pieces](image)

**2.2 Analysis procedure and result**

It's important to investigate a through-thickness distribution of grain shape and how the distribution changes as deformation increases, in order to predict the macroscopic deformation behavior of rolled sheet metal. In this work, for the purpose of quantifying grain shape, the grain oblatenesses for the surface and central parts were calculated by analyzing the microphotographs of material structures. The cross-sectional images were obtained using laser microscopy (Nikon NEXIV). Its image size and intensity were 610×480 pixels and 256 gray scale respectively. And the images were obtained by 50μm (near the surfaces of sheet) or 100μm through the surfaces A (compression side) and B (tension side) shown in Figure 1.

Figure 2 shows the images at compression side, center part and tension side for both test pieces before V-bending (a) and after V-bending (b). And then, the images were filtered to cut out high frequencies, enhanced edges and binarized. Grain boundaries were identified by the image intensity profiles. Finally, the oblateness $R$ was defined as the ratio of mean intercept length which was average distance between the intersections of scanline and grain boundary. The number of scanlines was about tens to hundreds for both longitudinal and through-thickness direction. Here, as $l_x$ and $l_y$ were defined as mean intercept length for longitudinal and through-thickness direction respectively, oblateness $R$ was

$$R = \frac{l_y}{l_x}.$$

It was expected that the result of analyzing grain oblateness would be unstable where the number of scanlines was small. Hence we confirmed that taking more than 100 scanlines was required.

In Figure 3 value of oblateness $R$ was larger than...
the one before bending and grains were elongated through the thickness of sheet metal at compression side. It seemed that this result corresponded to the images shown in Figure 2. On the other hand, at the tension side, change in grain oblateness between test pieces before bending and after bending couldn’t be seen. This didn’t correspond to Figure 2. In order to improve the precision of analyzing the oblateness, it’s necessary to improve the polished surfaces of the test pieces, and review the algorithm to identify the grain boundaries.

3. CYCLIC NANO-INDENTATION

3.1 Principle of nano-indentation and experimental setup

![Figure 4 Load and indentation depth curve](image)

Nano-indenteter is a high precision instrument for the determination of the nano mechanical properties such as Young’s modulus and hardness. An indenter tip with a known geometry is driven into the sample by applying an increasing load up to some preset value. The load is then gradually decreased until partial or complete relaxation of the sample has occurred. The load and indentation depth are recorded continuously throughout this process to produce a load and indentation depth curve (Figure 4) from which the nano mechanical properties such as Young’s modulus and hardness of the sample material can be calculated as following,

\[ E_s = \frac{\sqrt{\pi}}{2A(h)}S, \quad H = \frac{P}{A(h)} \]

where \( S \), \( P \) and \( A(h) \) denote contact stiffness, indentation load and contact area between the sample and indenter tip respectively.

In this experiment, nano-mechanical test instrument (Triboscope (Hysitron Inc.), SPM-9500J2 (SHIMADZU)) was employed. The configuration and specification of experimental setup were shown in Figure 5 and Table 1 respectively.

![Figure 5 Configuration of nano-indenter](image)

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<tr>
<th>Table 1 Specification of nano-indenter</th>
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<td>range</td>
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<td>Force</td>
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3.2 Cyclic nano-indentation

For a load and indentation depth curve as shown in Figure 4, Young’s modulus is calculated by initial gradient in unloading process. If indentation causes sample yielding, Young’s modulus means material properties after yielding. Then Young’s modulus under any value of plastic strain can be measured where indentation depth is controlled.

![Figure 6 Load-unload function in cyclic nano-indentation test](image)

In this experiment, Cyclic load and unload function shown in Figure 6 was performed, by which Young’s modulus and hardness were calculated for each unload process with different maximum
indentation load. As maximum indentation load increases, value of plastic strain caused by indenter tip on the surface of samples is getting larger. As the result, we can clarify the relationship between each Young's modulus (and hardness) and maximum indentation load. The load and indentation depth curve obtained by this load and unload function in cyclic indentation was shown in Figure.7. In this paper, we showed the result for the test piece before bending.

Moreover, Figure.8 shows the relationship between Young's moduli and maximum indentation load obtained from curves at each cyclic step shown in Figure.7. Figure.9 shows the relationship between the hardness and maximum indentation load.

As shown in Figure.8, the scatter of Young's modulus was large where maximum indentation load was less than 1000 μN. Though we couldn't find peculiar tendency, stable value of Young's modulus was measured where maximum indentation load was larger than 1000 μN. First, thinkable main factor resulting in scattering of Young's modulus was surface roughness of the test pieces. The influence of surface roughness on contact area between the test pieces and indenter tip will be larger where indentation depth was small. And the contact area was associated with Young's modulus calculated.

As to hardness shown in Figure.9, however, it decreased gradually where maximum indentation load is larger than 500 μN. It appeared that the effect of oxide film lead to increase in hardness at early stage.

4. CONCLUSION

In this work, we evaluated the through-thickness distributions of grain shape and its change caused by plastic deformation by analyzing microphotographs of material structure.

We investigated the relationship between Young's modulus and hardness and the plastic strain by cyclic nano-indentation testing. Consequently, it was seen that hardness decrease as plastic strain increase.

In the future, we'll investigate the relationship between the change of distribution of Young's modulus and hardness and the plastic strain caused by bending through the thickness of steel sheet.

Reference