Examination of Evaluation Method of Uniaxial Compressive Property of Cold-formed Duplex Embossed Sheet Metal by FEM Analysis

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Abstract. The utilization of applying periodic configurations to flat sheet metal will become a good method to enhance functional and mechanical properties. Especially, these periodic convexities and concavities of sheet metals are very good in enhancing functional property, such as heat radiation, improving of heat diffusivity, sound insulation and so on. In addition, this particular shape can also increase bending rigidity. In order to promote development of industrial technology for forming such sheet metals, it is necessary to offer information on the plastic feature of them. Here, this study focuses on sheet metal forming properties of a duplex embossed sheet, which has periodic convexities and concavities. And FEM analysis was carried out to attempt to conduct the uniaxial compression test used duplex embossed sheet by Blank holder force method which was got some inspirations from the method reported by Prof. Kuwabara. Based on analytical results, comparing the strain-stress responses and the equivalent strain maps which were obtained from uniaxial tension to those from uniaxial compression, it was found that embossing periodic structure itself had tension-compression asymmetry (SD effect).

1. Introduction

Embossing process is an advanced process which can enhance functional and mechanical properties. This process have been applied to ultrahigh strength steel sheet and deformed it to column. About dynamic crushing test of such duplex embossed sheets, it was confirmed that they have a good energy absorption ability and is possible to realize lightweight [1]. And the formability will be enhanced after sheet metal subjected to embossing and restoration process in a suitable condition [2]. Because of these merits, for example, this sheet metal has been applied to be formed as heat-insulators and heat-diffusers, which are components of automotive and mechanical devices. Recently, some attempts to make product from such sheet metals with periodic convexities and concavities have been tried in industrial press shops. However, fundamental feature of apparent plasticity of such sheet metals have not been clarified. In order to promote development of industrial technology for forming such sheet metals, it is necessary to offer information on the plastic feature of them. Here, this study focus on sheet metal forming properties of a duplex embossed sheet, which has periodic convexities and concavities structure.
About the apparent mechanical characteristic of such duplex embossed sheet have been investigated through uniaxial tensile test. From results, a new kind of anisotropy which depends on this sub-macroscopic embossing structure was confirmed [3]. Moreover, the evaluation of yield locus which is effected from this periodic embossing structure was also investigated [4]. Additionally, about the apparent work-hardening behavior, formability of duplex embossed sheet which was evaluated by Swift deep drawing test have been attempted to develop deep drawing method and to evaluate flange deformation behavior have been reported [5]~[8].

From results shown in such preceding studies, it is considered that not only tension behavior but also compression behavior of embossed sheet would be different from that of flat sheet. Apparent compression properties, which related deeply to such as Strength Differential effect (SD effect) and Bauschinger effect, of embossed sheet metal are very interesting to develop sheet metal forming methods for such sheets. Therefore, in present study, FEM analysis of uniaxial compression test used duplex embossed sheet was conducted to develop an investigation method of uniaxial compressive properties.

This study examined uniaxial compression method of a duplex embossed sheet referred to a compression method of flat sheet metal reported by T. Kuwabara [9]. Duplex embossed sheet was assumed to make by a cold punch stretching process, and were virtually produced in process simulation in order to reflect the localization of strain and strain-hardening which would occur in actual duplex embossing process. In this process of simulation, duplex embossed sheets were made from an aluminum strip. Finally, compression test was simulated thorough blank holder method. Based on results obtained from FEM simulation, the effect of blank holder force on duplex embossed sheet was investigated, and an optimal condition to get the closest results to uniaxial compression property was obtained. Moreover, the anisotropy which depends on embossing direction of embossed sheet was confirmed. Additionally, by comparing results obtained from uniaxial tension to those from compression of annealing embossing model (shape only) and work-hardening embossing model (with work-hardening), it was found that embossing periodic structure itself has tension-compression asymmetry (Strength differential effect : SDE).

2. Analytical method

2.1 Duplex embossing process

Figure 1 shows the duplex embossing apparatus and processing used multi-punches in this FEM simulation. About duplex embossing process, there are many hemispherical punches with diameter of 2 mm were fixed in a lattice pattern on the upper die and lower die. Moreover, punches on the upper die were corresponded the centre of punches on the lower die. When apply duplex embossing, the specimen was placed on the lower die, and the upper die was moveable in vertical direction and pushed down into the lower die. Here, half of push-down distance of upper die was defined as embossing height. Moreover, it is considered that characteristic of this quasi-uniform structure depends on this periodic arrangement of convex-concave shape. As shown in figure 2 and 3, center distance of two adjacent different orientation bosses was 3mm. Direction of center line of bosses in the same orientation (convexities or concavities) was defined as embossing direction. And the angle between uniaxial force direction and embossing direction was defined as embossing angle $\beta$.

2.2 Analytical condition

In this present study, a quarter-size specimen with solid elements were used as a model in simulation in order to reduce computational time. Although sheet metal used in the experiments had anisotropy itself, in this study, isotropic material was assumed in the simulations in order to investigate the effects of this periodic embossing shape only. Work hardening rule of Hollomon power law was applied whose flow curve satisfies the equation $\sigma = Fe^\delta$. Here, $F$
means plastic coefficient and \( n \) means strain-hardening coefficient, respectively. Young’s modulus \( E \), \( F \) and \( n \) of initial sheet metal was set as 69 GPa, 155 MPa and 0.2757, respectively. Specific material parameters and analytic parameters are listed in Table 1. FEM simulation conducted in this study were undertaken utilizing SIMUFACT 13.0.

3 Analytical procedure and result

3.1 Validation of analysis

Firstly, uniaxial tension of embossed sheets and plain sheet were conducted experimentally, which were in order to verify the validation of FEM simulation. Figure 4 shows the stress-strain responses obtained from experiments and FEM simulations of plain sheet and embossed sheets, respectively. From these results, it can be confirmed that, yield strength of plain sheet can be enhanced significantly after being subjected to duplex embossing process. Also, for embossed sheets, yield strength in case of \( \beta = 45^\circ \) is larger than that of \( \beta = 0^\circ \). Moreover, the analytical results of embossed sheets have slightly larger yield strength than that of experimental results. But they are matched well and in a good agreement with each other.

3.2 Blank holder method for compression test

About the method of uniaxial compression test. Here, in this present we referred from compression method of plain sheet reported by Prof. Kuwabara [9]. As shown in figure 5, a duplex embossed specimen, it is sandwiched between two comb-shaped blank holders. Next, subject blank holder force (BHF) to compress embossed specimen in order to prevent the buckling appearance. Then start to compress the specimen in longitudinal direction.
Figure 4. The stress-strain curves obtained from experiment and FEM analysis for uniaxial tension test.

Figure 5. Schematic of uniaxial compression method of duplex embossed sheet.

3.2.1 Effect of BHF on tension stress-strain curves

It is essential to investigate the effect of BHF on uniaxial property due to BHF can affect the states of stress and strain. As preliminary simulation, uniaxial tension were conducted analytically. BHF is 0kN, 0.1kN, 0.2kN, 0.3kN, respectively. From these results, stress-strain response of respective BHF conditions were compared. Figure 6 shows comparative stress-strain curves for different BHF on two different duplex embossed sheet (β = 0° h = 1mm, β = 45° h = 1mm). For both embossing angle β = 0° and β = 45°, their graphs exhibit just slightly different between BHF is 0kN and 0.1kN, whereas the difference at yield point become more and more significant as BHF increased. It is considered that in case of BHF is 0.1kN, there almost have no effect of BHF (surface pressure) on stress-strain response.

3.2.2 Analytical results of compression tests

It have been investigated about the effect of work-hardening derived from embossing process [5]. Therefore, in this present study, we also divided the investigation into two pattern. One is using work-hardening model, the other one is using annealing model (embossing shape only). Figure 7 shows the comparative analytical result of work-hardening result for uniaxial compression and tension on two different embossing arrangements. Observing the nominal stress-strain curves of compression and tension, it can be found that embossing work-hardening model almost shows no SD effect. Moreover, comparing these curves with different embossing angle. It can be confirmed that yield point and plastic deformation resistance of embossed sheet with 45° arrangement is obviously larger than that of 0° arrangement.

On the other hand, the analytical result of annealing for uniaxial compression and tension test on two different duplex embossed sheets were shown in figure 8. Different from that of work-hardening model, for annealing model, results exhibit a define SD effect in case of both β is 0° and 45°; the compressive nominal stress-strains (especially yield point) are obviously larger than in tension for embossed sheet.
Figure 6. Tension stress-strain curves of duplex embossed sheets in case of different BHF condition.

Figure 7. The stress-strain curves of uniaxial compression and tension test for work-hardening model.

Figure 8. The stress-strain curves of uniaxial compression and tension test for annealing model.

Furthermore, comparative stress-strain curves for uniaxial compression on two different embossed sheets model were shown in figure 9. The same with that of uniaxial tension, it can be clearly found that flow stress of work-hardening model is larger than that of plain sheet, and annealing model is clearly smaller than that of plain sheet. It is thought that this difference of flow stress is caused by work-hardening derived from embossing process. Also, focus on the results for the same model with different embossing angle, it can be found that compressive flow stress of 0° is smaller than that of 45°. Especially, this tendency of work-hardening model is more obvious than that of annealing model. It thought to be the representative anisotropy of this periodic 3D feature. Furthermore, Table 2 shows the equivalent strain distribution of uniaxial compression and tension on two different duplex embossed sheets in case of $\varepsilon$ is 5%. From these distributions, it can be found that both of $\beta$=0° and 45°, no matter for uniaxial tension or compression, the equivalent strain at the region between the bosses become the biggest and connected with each other.

4 Conclusion and outlook

In present study, FEM analysis of uniaxial compression and tension tests on two different models
(work-hardening and annealing) of duplex embossed sheet were conducted to develop an evaluation method of uniaxial compression properties. The dependency (anisotropy) of flow stress-strain response on embossing arrangement was analyzed. By using work-hardening and annealing models of duplex embossed sheets, SD effect of this periodic 3D embossing structure become more obvious to be observed. It is also become a validation of experiment in the future. Future work includes the make dies for uniaxial compression of embossed sheet. And based on it, investigate the uniaxial compression feature of duplex embossed sheets experimentally. Also this test will be extended to investigate about the Bauschinger effect derived from duplex embossing structure.

Figure 9. The stress-strain curves of uniaxial compression on work-hardening and annealing model.

Table 2. Equivalent strain distribution of uniaxial compression and tension for duplex embossed sheets

| Compression | Tension |
|-------------|---------|
| (a) $\beta = 0^\circ$ $h = 1\text{mm}$ $\varepsilon = 5\%$ | (a) $\beta = 0^\circ$ $h = 1\text{mm}$ $\varepsilon = 5\%$ |
| (b) $\beta = 45^\circ$ $h = 1\text{mm}$ $\varepsilon = 5\%$ | (b) $\beta = 45^\circ$ $h = 1\text{mm}$ $\varepsilon = 5\%$ |

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