Technical Report

Work-hardening Behavior and Springback Simulation of Lean Duplex Stainless Steel (NSSC 2120™)

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Abstract

Lean duplex stainless steel (NSSC 2120) has excellent corrosion resistance and strength, and its applications in the market are expanding. This article investigated springback, which is problematic in the bending of thin sheets of NSSC 2120, by focusing on work-hardening behavior. An analysis of forming simulations and the results of improvement measures are reported. NSSC 2120 causes remarkable elastic recovery in the draw-bent forming and therefore the springback is larger than that of SUS304, a representative stainless steel. Springback simulations were conducted using the Yoshida-Uemori kinematic hardening rule, and the experimental and calculation results were in good agreement. The optimizing of die clearance was proposed as the forming condition reducing springback. The experiment in draw-bent forming was conducted using the same clearance as the sheet thickness, and a reduction in springback was confirmed. We will implement processing solutions using simulations and will continue to increase the applications.

1. Introduction

The main constituent elements Cr, Ni, and Mo of stainless steels are all included in the seven types of metals stored in the national stockpile in Japan.[1] Particularly, Ni and Mo are so scare that their prices fluctuate widely to the detriment of the price stability of stainless steels. The most common grade of stainless steel is the metastable austenitic stainless steel SUS304. It contains about 8% of Ni. As the Ni price fluctuates, therefore, the price of the SUS304 fluctuates in synchronism. In 2007, the price of the SUS304 rose so much that it caused problems. To deal with such price fluctuations and to prevent the depletion of principal elements, Nippon Steel Stainless Steel Corporation has developed ferritic stainless steels and duplex ferrite-austenite stainless steels (duplex stainless steels) to replace the SUS304. To expand the market for these stainless steels, we are laboring to develop forming solutions as represented by the proposal of forming conditions.

The composition of the lean duplex stainless steels (NSSC 2120, UNS82122, and SUS821L1)[2] developed as substitutes for the SUS304 is characterized by lower contents of rare alloy elements than in the existing duplex stainless steels. They also have higher strength than the SUS304 and are expected to enable thickness and weight reduction. On the other hand, poor shape accuracy due to an elastic recovery phenomenon (springback) after removal from tools has emerged as a serious problem. Since springback is a common issue for high-strength steels, many efforts have been made to solve it.[3] In this report, we describe the results we have achieved regarding the springback behavior of the NSSC 2120 and springback reduction measures we have developed by using forming simulation.

2. Experimental Methods and Results

2.1 Experimental material

The representative chemical composition of the experimental material NSSC 2120 is shown in comparison with that of the SUS304 in **Table 1**. The microstructure of the NSSC 2120 is shown in **Fig. 1**. Its chemical composition is characteristic in that the Ni

Table 1 Chemical composition

(mass%)

	C	Mn	Ni	Cr	Cu	N
NSSC 2120	0.01	3.0	2.1	21.0	1.0	0.17
SUS304	0.05	1.0	8.1	18.1	0.2	0.04

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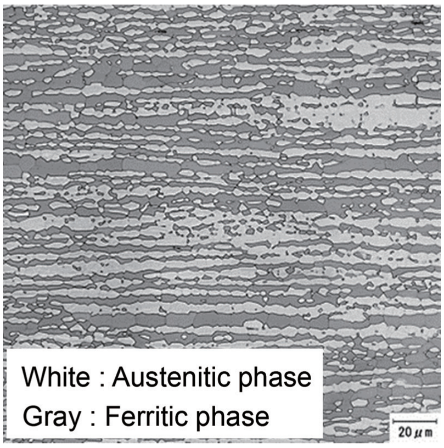

Fig. 1 Microstructure

content is 2.1%, about 6% lower than that of the SUS304, and that 0.17%N is added to stabilize the austenite phase. The microstructure consists of ferrite and austenite phases at about 50% each, is layered, and has fine grains elongated in the rolling direction.

2.2 Experimental items

Two experiments were conducted: (1) tensile test and (2) draw-bending test (for springback evaluation).

2.2.1 Tensile test

A Shimadzu AG-100 kNX universal testing machine was used in the tensile test. JIS No. 13 B test specimens were taken parallel to the rolling direction. Fracturing of the specimens was performed at a crosshead speed of 20 mm/min to obtain their tensile properties. Furthermore, nominal stress-nominal strain diagrams were prepared from the displacement and load values.

2.2.2 Draw-bending test (for springback evaluation)

A draw-bending test was used to evaluate the springback. The tools shown in **Fig. 2** were installed in an Erichsen 145-60 testing machine. Strip specimens measuring 20 mm wide and 130 mm long (in the rolling direction) were tested. Johnson Wax #122 was applied only to the die side to reduce the effect of friction between the tools and the blanksheet. The blank holding force was set to 10 kN and the punch speed was set to 0.167 mm/s. The blanksheet was formed to a height of 40 mm. The deformation of the material as it was removed from the tools was defined as springback. The hardness at the mid-plane of the test formed parts was measured in the wall thickness direction from the central die shoulder. The test load was 1 kgf and the measurement interval was 1 mm.

2.3 Experimental results

2.3.1 Tensile properties and work hardening behavior

The tensile properties and nominal stress-nominal strain diagram of the NSSC 2120 are shown in comparison with the SUS304 in **Table 2** and **Fig. 3**, respectively. The NSSC 2120 has a 0.2% proof stress of over 600 MPa and an elongation of about 30%. It has higher strength, lower ductility, and smaller work hardening than the SUS304. These tensile property differences may be ascribed to: (1) higher N content and (2) finer grain size resulting from the duplex microstructure.

2.3.2 Springback evaluation (draw-bending test)

Figure 4 shows a drawn-bent NSSC 2120 specimen as compared with a drawn-bent SUS304 specimen. The side wall bend that indicates the springback is greater for the NSSC 2120 than for the SUS304. The opening width (ΔW) is also larger than the NSSC 2120. **Figure 5** shows the measured hardness distributions of the

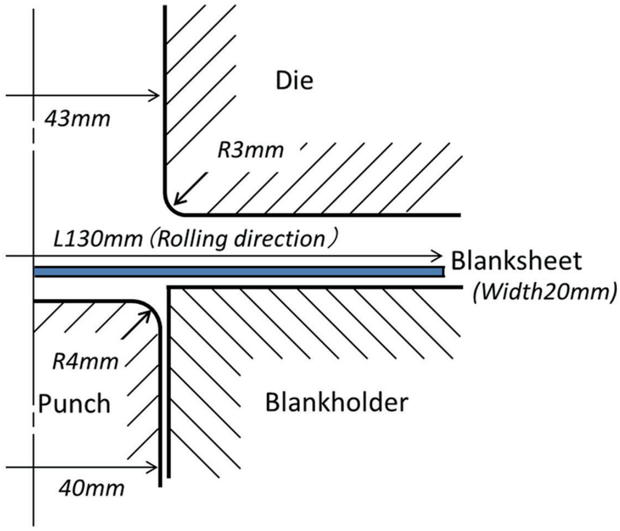

Fig. 2 Experimental set-up and specimen for draw-bending

Table 2 Results of tensile test (Specimen: JIS13B, RD)

	0.2%PS MPa	TS MPa	El %	U-El %	n-value
NSSC 2120	613	809	29	20	0.20
SUS304	300	678	51	48	0.46

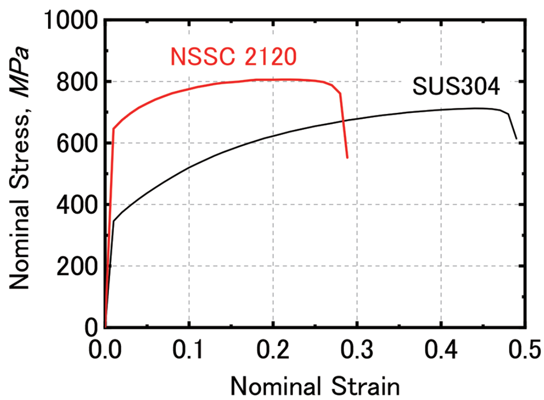

Fig. 3 Stress–strain curves of SUS304 and NSSC 2120

draw-bending test specimens. Although the work hardening of the side wall in draw-bending can be confirmed for the NSSC 2120, the hardness increase of the NSSC 2120 is smaller than that of the SUS304. The difference in the work hardening behavior occurred from the bending and unbending of the die shoulder area.

3. Discussion

3.1 Springback and work hardening behavior

The springback difference between the NSSC 2120 and the SUS304 is considered reasonable, reflecting the differences in the tensile properties between the two.[4] In other words, when the higher-strength steel NSSC 2120 was formed, its strength increased to increase the elastic recovery amount and hence the springback amount. The factors for the difference in work hardening after the draw-bending test may be considered as follows: the work harden-

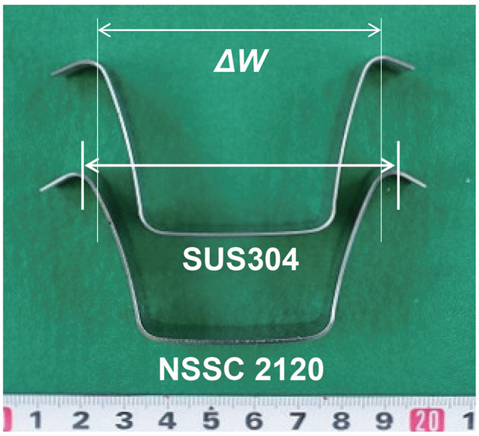

Fig. 4 Springback behavior after draw-bending test

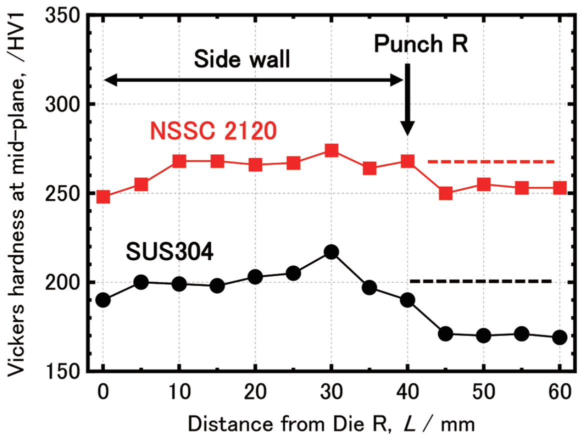

Fig. 5 Distribution of hardness after draw-bending at side wall

ing coefficient (n-value) of the NSSC 2120 was smaller and its 0.2% proof stress was higher. The bend radius at the die shoulder consequently became larger than that for the SUS304. This is considered to have created the difference in the amount of strain introduced by bending and unbending.

3.2 Simulation of springback by Yoshida-Uemori model

To accurately reproduce the springback behavior by simulation, it is necessary to accurately reproduce the work hardening behavior when tension and compression are cyclically applied. Many reports[5] have been published on techniques for predicting the springback of high-strength steels. The springback can be predicted with high accuracy by the simulation. In this report, we used the Yoshida-Uemori model (the Y-U model).[6] The PAM-STAMP 2G was used as the solver.

The true stress-true strain diagrams experimentally obtained under uniaxial and under cyclic tension and compression are shown in **Fig. 6**, as compared with those obtained by the simulation with the Y-U model. The stress and strain relationships simulated with the Y-U model agree well with the experimental ones. The Bauschinger effect when the load was reversed from tension to compression is also accurately reproduced. We calculated the springback in the experiment by using the material parameters obtained by the simulation. The simulation conditions are shown in **Table 3**. The shapes of the tools shown in Fig. 2 were applied to the simulation. The results of the simulation with the Y-U model and the experimental results

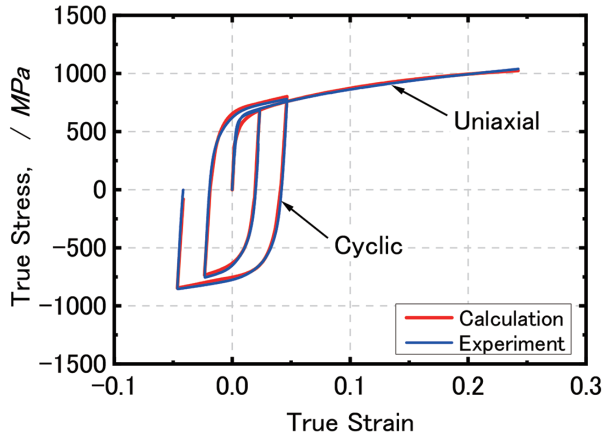

Fig. 6 Accurate prediction of work-hardening behavior by FEM simulation (NSSC 2120)

Table 3 Simulation conditions

Tickness mm	Mesh size mm	BHF kN	Friction coefficient	Forming height	Model
1.0	1.0	10	0.06	40	shell

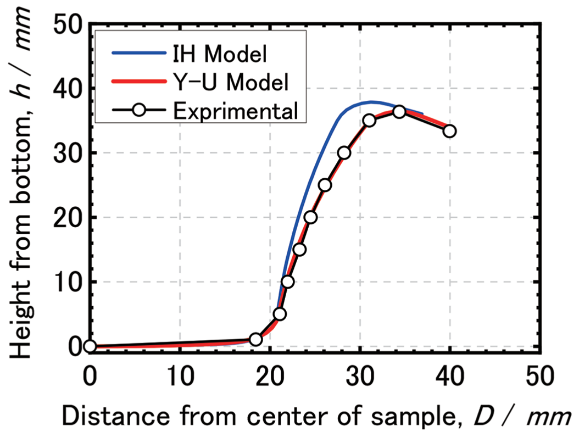

Fig. 7 Comparison of experimental and springback simulation using the Yoshida-Uemori model (NSSC 2120)

are comparatively shown in **Fig. 7**. The results of the simulation with the Y-U model agree with the experimental results with high accuracy. Their differences from the results of calculation with the isotropic hardening (IH) model are also apparent. From these results, we judged that we could reproduce the springback behavior by the simulation. We thereupon studied the forming conditions for improving the springback.

3.3 Forming conditions to reduce springback

The springback that occurs in bent sheet metal parts reduces their dimensional accuracy. Various measures are examined to counter this situation.[7] The springback that occurs in the drawn-bent parts as investigated in this study is generally the outward deformation of the parts when removed from the tools after being subjected to bending and unbending strains at the die radius. The two experimental parts shown in Fig. 4 are similarly deformed. Optimization of the die shoulder radius and metal sheet thickness (rd/t),[8] step drawing,[9] and shape fixing beads[8] are among the measures taken to reduce the springback due to such wall warping deformation. Although these measures are expected to improve the springback, we studied how to improve the springback by changing the punch-die clearance. Our aim was to achieve both formability and springback reduction. Because a punch-die clearance less than the sheet thickness had the effect of ironing, it was set to 1.0 mm and was the same as the thickness of the steel sheet specimens used in this study. **Figure 8** shows the results of the simulation with the punch-die clearance set to 1.0 mm. Reducing the punch-die clearance from 1.5 mm to 1.0 mm improved the springback. **Figure 9** shows the factors that may have improved the springback. As the bend radius at the die shoulder decreased and the friction force between the part side wall and the tools increased, the material flow was hindered, and the tension increased between the die face and the punch shoulder. **Figure 10** compares the bend radius of the material at the die shoulder at a forming height of 20 mm for punch-die clearances of 1.0 and 1.5 mm, respectively. The bend radius is smaller for the punch-die clearance of 1.0 mm than for the punch-die clearance of 1.5 mm. The amount of strain is considered to have increased during the bending and unbending deformations. **Figure 11** shows the stress distribution in the side wall at the bottom dead center obtained by the simulation. Setting the punch-die clearance to 1.0 mm is confirmed to change the stress distribution in the side wall to uniform distribution and to increase the stress in the side wall. These results suggest that the springback is improved by the increase in the tensile stress of the side wall.

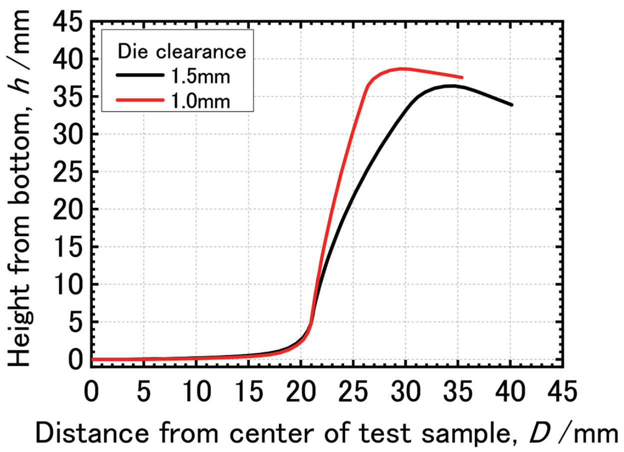

Fig. 8 Effect of die clearance on springback after draw-bending by FEM simulation (NSSC 2120)

3.4 Verification experiment

To verify the simulation results described in the previous section, we conducted a draw-bending test with the punch-die clearance set to 1.0 mm. This clearance was the same as the test sheet thickness. The results are shown in **Fig. 12**. Reducing the punch-die clearance reduced the springback. This is presumably the effect of the increased tensile stress in the side wall as obtained by the simulation.

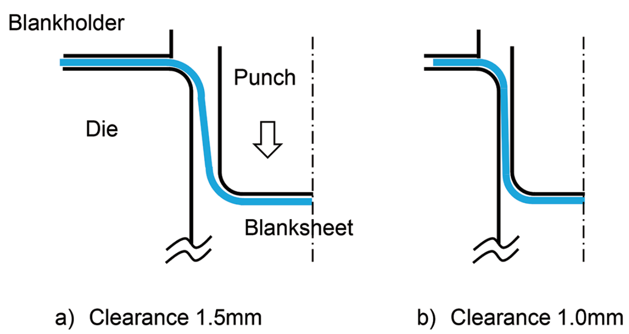

Fig. 9 Effect of die clearance on bend radius at die shoulder on draw-bending

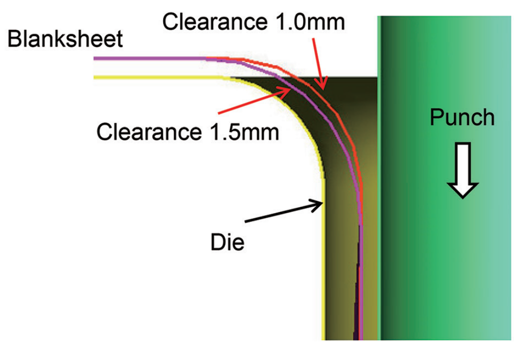

Fig. 10 Effect of die clearance on bend radius at die shoulder by FEM simulation

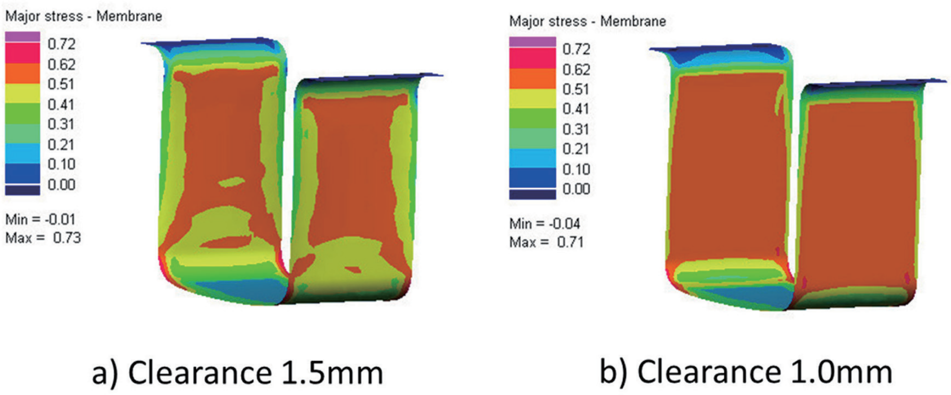

Fig. 11 Effect of die clearance on major stress at sidewall after draw-bending by FEM simulation (NSSC 2120)

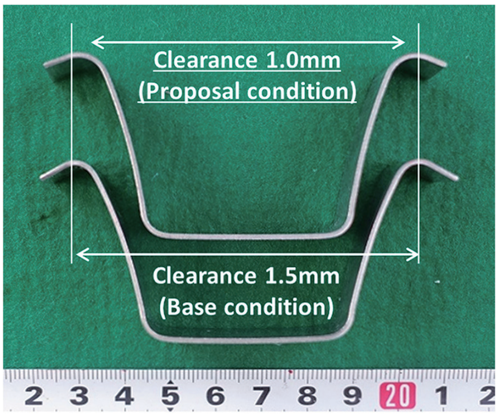

Fig. 12 Effect of die clearance on springback after draw-bending

4. Conclusions

We analyzed the springback of the lean duplex stainless steel NSSC 2120 by accurately reproducing the work hardening behavior by the simulation. We obtained the following findings:

1) The NSSC 2120 exhibits higher strength and lower ductility than the SUS304. Its springback during the draw-bending test is larger.
2) Comparison of the work hardening in the side wall after the draw-bending test shows that the work hardening of the NSSC 2120 is smaller than that of the SUS304.
3) The springback behavior of the NSSC 2120 can be predicted with high accuracy by applying the Y-U model.
4) We proposed changing the punch-die clearance as one method to improve the springback of the NSSC 2120 and confirmed its effectiveness by a verification experiment.

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