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Deformation-induced martensitic transformation behavior of type 304 stainless steel sheet in draw-bending process

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ABSTRACT

Deformation-induced martensitic transformation and workhardening behavior in draw bending process was investigated, on a Type 304 stainless steel sheet, in comparison with that in uniaxial tension experiments. The Vickers hardness of the draw-bent sheet at the surface is much larger than that at the mid-plane, and it becomes remarkably larger with increasing blank holder force. The significant increase of hardness in the deformed sheet is due to α'-martensitic transformation. The volume fraction of α'-martensite in the draw-bent sheet is smaller than that in the uniaxially pulled sheet with the same plastic strain. In uniaxial tension the sheet is plastically deformed in one direction monotonically, but in contrast, in draw-bending tension-to-compression (i.e., bending-to-unbending) deformation takes place when the sheet is drawn over the die-corner. The difference in the evolution of the martensite between draw-bending and uniaxial tension is explained from such a difference in deformation mode. Under cyclic deformation, in the reverse deformation, the martensitic transformation stagnates in a certain extent of plastic strain because of the Bauschinger effect. Including such a case of stress reversal, the evolution of the martensitic transformation is given as a unique function of the effective stress, rather than the effective plastic strain. Thus the behavior of the martensitic transformation of the material during plastic deformation would be understood from the stress-induced phase transformation mechanism.

1. Introduction

Austenitic stainless steels are widely used in many fields of industry because of their excellent mechanical and functional properties, such as high ductility and high strength, as well as excellent corrosion and heat resistances. Type 304 steel, one of the most popular austenitic stainless steel, has a very high formability, e.g., over 50% elongation is possible under uniaxial tension (Fukase et al., 1968), owing to the deformation-induced α'-martensitic transformation (Tamura et al., 1966). However, when using such a hard sheet metal for press forming operation, one may encounter some difficulties, such as large springback (Ohashi et al., 1977) and die galling (Hyashi, 1977). In addition, the risk of delayed cracking in deep-drawn cups becomes higher with increasing α'-martensite volume in the formed products (Sumitomo et al., 1976).

Therefore, in order to predict the formability of type 304 stainless steel sheet, it is of vital importance to have a model describing the evolution of α'-martensitic phase. A model of the kinetics for the deformation-induced martensitic transformation was first proposed by Olson and Cohen (1975), and later the strain rate effect was considered in the model by Stringfellow et al. (1992). In these models the volume fraction of the transformation-induced martensite is expressed as a function of accumulated plastic strain. However, there are some articles reporting that the evolution of the martensite is not only a unique function of plastic strain but it is also dependent on deformation mode. Hamasai et al. (2014), recently found that the martensitic phase transformation behavior under cyclic deformation is not the same as one under uniaxial tension.

Accordingly, in the present study, the martensitic transformation behavior of type 304 stainless steel sheets during draw-bending process, where a sheet is subjected to bending-unbending when the sheet is drawn over the die corner, is investigated. The Vickers hardness distributions along the sheet thickness were determined for drawn sheets for several levels of blank holder force (BHF). The volume fractions of α'-martensite were measured both at the surface and the mid-plane of the drawn sheet for various BHFs, and they were compared to those obtained from uniaxially pulled specimens. From these, the effect of stress reversal on the martensitic transformation is discussed.

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Table 1
Chemical compositions (wt%).

C	Si	Mn	Ni	Cr	Cu	N
0.05	0.5	1.1	8.0	18.0	0.3	0.04

Table 2
Tensile properties (test specimen: JIS 13B).

0.2% Proof stress (MPa)	Tensile stress (MPa)	Elongation (%)	*n* Value (10–30%)
313	750	56	0.45

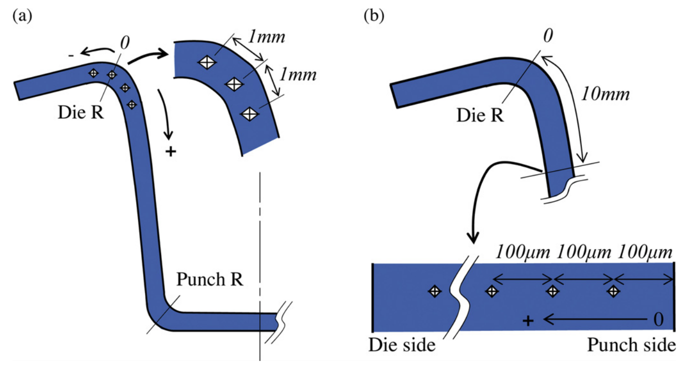

Fig. 2. Locations for micro-Vickers hardness measurement (a) in the longitudinal direction; (b) in the thickness direction.

2. Experimental procedure

2.1. Specimen

Type 304 stainless steel sheets of 1 mm thick (as annealed) was used for the experiment. Tables 1 and 2 show the chemical compositions (wt%) of the sheet and its tensile properties (test specimen: JIS 13B) in the rolling direction, respectively.

2.2. Draw-bending

The experimental set-up for draw-bending and the specimen is schematically illustrated in Fig. 1.

The draw-bending experiments were conducted for three levels of BHFs, (10, 30 and 50 kN). The specimen was drawn over the die-corner (die-corner radius was 3 mm) at a punch speed of 0.167 mm/s up to 40 mm punch travel, where a lubricant with high viscosity (Johnson wax no. 122) was applied on the die and blank holder surfaces.

2.3. Evaluation of materials completed testing

The volume fraction of the deformation-induced martensite at the surface of the specimen was measured using a ferrite meter (MP-30, Fischer Co. Ltd.). For an accurate determination of the volume fraction of the martensite phase, thus measured volume fraction of the martensite had been calibrated using the X-ray analysis. For calibration, cold-rolled samples with different α′-martensite volume fractions were employed. In the X-ray analysis, the volume fraction was calculated from integrated strength of γ (2 0 0) and α′ (2 1 1) using the target Cr-*K*α line with a micro point X-ray stress measurement device (PSPC-MSF, Rigaku Co. Ltd.).

In the analysis of α′-martensitic transformation behavior in the thickness direction, separation of the ferritic phase from the austenitic phase was performed by the Electron beam Backscatter Diffraction (EBSD) method using a field emission-type scanning electron microscope (JSM-7000F FE-SEM, JEOL Co. Ltd.). The EBSD measurement was conducted with an acceleration voltage of 25 kV at several locations along the sheet thickness direction starting from near the sheet surface (approximately 100 μm away from the sheet surface) to the mid-plane of the sheet with an interval of 0.5 μm.

Furthermore, hardness distributions in the sheet, both in the longitudinal and thickness directions, were determined by the micro-Vickers hardness measurement (HV0.1), as schematically illustrated in Fig. 2. In the longitudinal direction, the hardness at the mid-point of the sheet was measured throughout the side-wall of the draw-bent sheet (from the flange to the punch-corner) with an interval of 1 mm. In the sheet thickness direction, the measurement was conducted at a position of 10 mm away from the end of die-corner with an interval of 100 μm in the thickness direction from the surface to the mid-plane of the sheet.

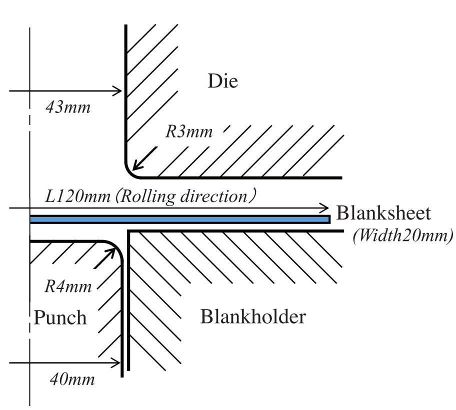

Fig. 1. Experimental set-up and specimen for draw-bending.

3. Results and discussion

3.1. Workhardening of draw-bent sheet

The specimens after draw-bending experiments are shown in Fig. 3, where one can see that the side-wall curl decreases significantly with increasing BHF since it gives a tensile load to the sheet, thus increasing tension over thickness and shifting the neutral line toward the die.

The hardness distributions of draw-bent sheets are summarized in Fig 4(a) and (b), where Fig. 4(a) shows the hardness at the mid-plane, and Fig. 4(b) the result in the thickness direction, for three

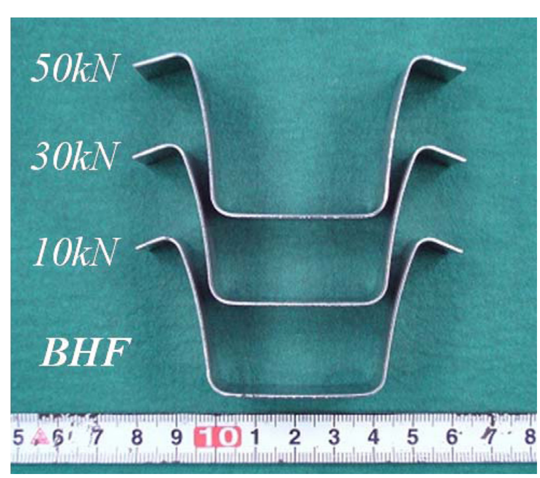

Fig. 3. Outlook of specimens after draw-bending experiments.