11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan

Method of reducing residual stress generated by laser cutting by light indentation of sheet metal edge

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Abstract

Laser cutting has started to be used as an effective method for cutting out blanks from rolled sheet metals because of its high flexibility for cutting line and high productivity. However, residual stresses, which are generated by laser cutting, have been the greatest obstacle for the popularization of laser cutting. One of the problems is the warp which appears in the sheet metal, after being subjected to bending processes after laser cutting. The authors present a light indentation method for reducing residual stress generated by laser cutting. The method is to give light indentation on the sheet metal edge and to reduce tensile residual stress generated near the laser cutting surface. In particular, this present paper especially focuses upon optimization of working condition depending on mechanical properties of blank. Furthermore, the mechanism of transition of stress and effective strain in light indentation was examined. Experiments of U-bending after applying light indentation were conducted for usability of this method. The FEM analyses were carried out in order to investigate the effect of working condition in various mechanical properties. As a result, the optimum condition of light indentation method in various materials was found out, and the warp of bent sheet metals was drastically reduced.

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Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Bending; Laser cutting ; Residual stress ;Warp;

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1. Introduction

Sheet metal bending is one of the most concise and common methods to produce frames, and various products. Although bending is simple, there are many problems in production. For example, although spring-back should be predicted or levelled for manufacturing precise products using bending, it is difficult because of kinematic hardening or the existence of free surface. The residual stress is another problem. Although the sheet metal might be flat and straight if the residual stress is well balanced, some warp or curvature might occur if the balance is disturbed by machining or metal forming including bending (Kazama et al., 2004).

Laser cutting has started to be used as an effective method for cutting out blanks from rolled sheet metals because of its high flexibility for cutting line and high productivity. However, the residual stresses, which are generated by laser cutting, have been the greatest obstacle for the popularization of laser cutting. (Ito et al., 2009). One of the problems is the warp which appears in the sheet metal, after being subjected to bending processes following the laser cutting (Jin et al., 2010). Leveler processing or annealing are known as effective methods to reduce residual stresses (Weiss et al., 2012). However, the equipment is large-scale and high-cost. Therefore, a simple and appropriate methods are required for the reduction of the residual stresses. Therefore, simple method has been demanded for reducing the residual stresses generated by laser cutting in sheet metal forming field.

The authors present a light indentation method for reducing residual stress generated by laser cutting. The method is to give light indentation on the sheet metal edge and to reduce tensile residual stress generated near the laser cutting surface. In particular, the present study focuses upon the effect of the working condition depending on mechanical properties of blank. Experiments of U-bending after applying light indentation were conducted for verifying the effectiveness of the proposed method. The FE analyses were carried out in order to investigate the optimum condition in mechanical properties.

2. Proposed method

2.1. Light indentation of sheet metal edge

When sheet metal is blanked by laser cutting, the residual tensile stress near the laser cut surface is generated, though the stress is well balanced. When the balance of the residual stress is disturbed by bending, the "ship-type" warp occurs as shown in Fig. 1(a). Tension leveler and stretch levelling are known as methods of reducing residual stress. However, as the equipment is extensive, there are problems in the cost and productivity.

In the proposed method, the sheet metal edge, which has been cut by laser, should be indented by a slight amount in the thickness direction. The slight thickness reduction elongates the sheet metal in width direction due to volumetric constancy, leading to relaxation of the tensile stress caused by laser cutting. The proposed method is schematically shown in Fig. 1(b). Experiments and FEM analysis were carried out to determine the proper conditions.

Fig. 1. Warp after U-bending and light indentation method. (a) Ship-type warp by U-bending, (b) process of light indentation method.
3. Experiment

3.1. Experimental procedure

The sheet metal, which had been sectioned out into rectangle shape by the laser, was subjected to the proposed method of light indentation. Then, the sheet metal was bent in the U-bending manner for the evaluation of the effect of the light indentation for levelling of the residual stress as shown in Fig. 1(a). The warp height $\delta_L$ was used as the index for the intensity of the residual stress because the warp height should increase with increase of the tensile stress along the laser-cut edge. Low carbon steel SPCC (JIS) and stainless steel SUS304 (JIS) were used in the experiment, the stress-strain diagrams of which are shown in Fig. 2. Stress-strain diagram was approximated by Swift’s law

$$\sigma = F(\varepsilon^p + \varepsilon_0)^n,$$

where $\sigma$ is the true stress, $\varepsilon^p$ is the plastic strain, $F$ is the hardening coefficient, $n$ is the hardening exponent, and $\varepsilon_0$ is the offset of yield strain. The sheet metal edge was pressed by the punch for the whole length in the longitudinal direction and for 2 mm in the width direction because the residual tensile stress is generated within the range of 2 mm from the laser-cut surface. The size of the laser-cut sheet metal was 400 mm in the longitudinal direction and 65 mm in the width direction. The flange length was 10 mm in the U-bending.

![Stress-strain diagram of sheet metals.](image)

3.2. Results of experiment

The relationship between the warp after U-bending and indent pressure is shown in Fig. 3. The warp height $\delta_L$ decreased with increase of the indentation pressure $P$ up to a certain optimum value. When the pressure $P$ exceeded the optimum point $P_o$, the sheet metal bent in the opposite way. The optimum values $P_o$ for the minimum warp height was 230 and 390 MPa for SPCC and SUS304, respectively. It seems that the harder material require the higher optimum indentation pressure $P_o$. The proof stress at 1% strain $\sigma_p$ in the stress-strain diagram was used as a reference value for the evaluation of the amount of the optimum indentation pressure $P_o$ because the stress-strain diagram generally becomes stable when the strain is larger than 0.5% and the deformation by the light indentation was less than 2%. As the proof stresses at 1% strain of SPCC and SUS304 were 192 and 370 MPa, it might be assumed that the optimum pressure $P_o$ should be equal to around 120% of the proof strain.
4. Analysis

4.1. FE analysis model and analysis condition

As it would be difficult for experiments to verify the assumption that the optimum pressure $P_o$ should be equal to around 120% of the proof strain at 1% strain, a series of the finite element analyses was carried out. The finite element analysis was conducted using the commercial code ELFEN, which was developed by Rockfield Software Limited. The FE analysis model in this method is shown in Fig. 4. In this FE analysis, initial temperature is given in the edge of sheet metal, and the sheet metal was cooled by air, resulting in the generation of the residual tensile stress similar to laser cutting in experiments. After that, residual stress is reduced by light indentation of the sheet metal edge.

The optimum indentation pressure $P_o$ might change depending on the residual stress generated by the laser cutting as well as depending on the mechanical properties. Therefore, the optimum pressure $P_o$ was sought out corresponding to the residual stress and the flow stress of the sheet material. The intensity of the residual stress was changed by controlling the initial temperature in Fig. 4(a). The maximum residual stress, which appeared at the edge of the sheet metal, was controlled from 190 to 280 MPa. On the other hand, the flow stresses were controlled by changing the coefficient of the stress-strain diagram assuming the following Swift’s law. (1)

Five sets of coefficients $F$ and $n$ were selected – $F$ ranges from 300 to 1500 MPa and $n$ ranges from 0.2 to 0.5 while $\varepsilon_0$ was fixed at 0.312. The obtained stress-strain diagrams, A – F, are shown in Fig. 5. The sheet metal was 50 mm in length, 30 mm in width and 1.2 mm in thickness.
4.2. Results of FE analysis and examination

The intensity of the residual stress were evaluated by the form of moment $M_{rs}$ calculated by

$$M_{rs} = \int_0^h t y \sigma_w dy,$$

where $t$ is thickness, $h$ is flange length and $\sigma_w$ is the residual stress in the longitudinal direction, which were shown in Fig. 1(a). The flange length $h$ is fixed at 10 mm as it is one of the standard values in industrial use. No warp appears just after laser cutting and before bending because the moments at the two sides of the sheet metal are in the opposite direction and the second moment of area is large in the in-plane bending direction. However, when the sheet metal is bent in the U-bending manner, the warp appears because the bending moments $M_{rs}$ at the two sides are in the same direction and the second moment of area is small in the out-of-plane bending direction.

The effect of the indentation pressure $P$ on the bending moment $M_{rs}$ was preliminarily investigated, though the graph was omitted in this paper. In the preliminary investigation, the maximum residual stress $\sigma_w$ was fixed at 190 MPa as the residual stress distribution was similar to the experimental value. The bending moment $M_{rs}$ decreased with increase of the indentation pressure $P$ in the similar way to the warp height $h$ which was shown in Fig. 3. The optimum indentation pressure was defined as the pressure which decreases the moment $M_{rs}$ to zero.

The relationship between the proof stress and the optimum indentation pressure is shown in Fig. 6 taking the maximum tensile stress generated by the laser $\sigma_{w\text{max}}$ as a parameter. It is revealed that the optimum indentation pressure $P_o$ is roughly proportional to 1% proof stress $\sigma_p$, and the proportion ratio $P_o / \sigma_p$ was 110–130 % regardless of the maximum residual stress from 190 to 280 MPa.

It might be important to clarify the applicability of the proposed method to various intensities of residual stress generated by the laser cutting. Although the residual stress might change depending on the laser cutting conditions, it would be difficult to measure the stress. Therefore, it would be ideal if the light indentation has a stable levelling effect of the residual stress regardless of the intensity of the residual stress.

Figure 7 shows the influence of the residual-stress intensity on the effect of the proposed method taking material D in Fig 4 as an example. The indentation pressure $P$ was determined as 310 MPa, which is 120 % of the 1 % proof stress $\sigma_p$ of 264 MPa. When the maximum residual stress $\sigma_{w\text{max}}$ is 190 MPa, which has a similar residual stress distribution to the experimental value, the bending moment $M_{rs}$ is certainly levelled to zero. Light indentation is a stable and effective method which can level the bending moment $M_{rs}$ less than 1/3 of the initial value within the very wide range of $\sigma_p$ from 130 to 280 MPa.
Fig. 6. Relationship between proper indentation pressure and 1% proof stress taking tensile residual stress as a parameter for the maximum residual stress at edge of 190 MPa.

Fig. 7. Relationship between maximum residual tensile stress and moment after light indentation with a fixed pressure, which was optimized for maximum residual stress of 190 MPa.

5. Conclusion

A method of reducing residual stress generated by laser cutting was proposed. The FEM analysis and experiment examinations verified the validity of this method. Results were as follows.
(1) The proposed method, which indents the edge of sheet metal, was drastically effective for levelling the warp.
(2) The optimum indentation pressure \( P_o \) is proportional to 1% proof stress \( \sigma_p \), and the proportion ratio \( P_o / \sigma_p \) was 110~130 % regardless of the maximum residual stress.
(3) The proposed method is ideal as it has a stable levelling effect of the residual stress regardless of the intensity of the residual stress.

References