Suppression of serration of Al-Mg sheet by periodic indentation

H Utsunomiya¹, N Ochi¹, S Koshi¹, K Natori¹ and R Matsumoto¹

¹ Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, 565-0871, Japan

uts@mat.eng.osaka-u.ac.jp

Abstract. Al-Mg alloy sheets often exhibit surface defects, e.g., stretcher strain, after sheet metal forming. The surface defects are formed by nonuniform deformation due to the dynamic strain aging where serrations appear on stress-strain curves in tensile test. In order to suppress the nonuniform deformation, the authors propose periodic micro indentation on sheet surface in this study. Four Al-Mg alloy sheets were subjected to the tensile test after the indentation. Strain gauges on specimen surface were used to investigate the evolution of local strain. It is concluded that the periodic indentation can suppress nonuniform deformation.

1. Introduction

Al-Mg alloy sheets often exhibit nonuniform deformation at room temperature. Surface defects, i.e., ridging/roping or stretcher strain are caused by the nonuniform deformation. They are industrial problems in sheet metal forming process because the defects deteriorate deformability of the sheets as well as surface quality of the formed products. Various investigations were conducted to reveal the formation mechanism of the surface defects [1-3] and forming conditions, e.g., temperature [4], strain rate [5] and microstructure [6]. It was reported that the dynamic strain aging or Portevin-LeChatelier effect of Mg atoms is a metallurgical mechanism and that the nonuniform deformation appears by the intermittent propagation of deformation bands. Accordingly, stress oscillation, i.e., serrations appear on stress-strain curve in tensile tests. This paper reports that periodic micro indentation on sheet surface induces uniform deformation and reduces the serrations.

2. Experimental

AA5182-O aluminum alloy (Al-4.55mass%Mg) sheets with a thickness of 1.00 mm were mainly used in this study. The sheets showed fully recrystallized microstructure with mean grain size of 16.6 μm. In order to investigate the effects of Mg content, three other Al-Mg alloy, i.e., AA5052-O (Al-2.5mass%Mg), AA5154-O (Al-3.5mass%Mg), and AA5022-O (Al-4.2mass%Mg), sheets were also used. The thicknesses of the alloy sheets were 0.93 mm, 1.60 mm, and 1.00 mm, respectively. Dumbbell-shaped tensile specimens with a parallel part of 24 mm in length and 10 mm in width were prepared by an electric discharge wire-cutting machine. The gauge length (GL) of 20 mm was marked in the parallel part.

Micro indentation with a grid spacing of λ=283, 400, 566 or 800 μm was applied to the specimen surface as shown in figure 1 using an automatic micro Vickers hardness tester, Mitutoyo Corp., HM-200, at a load of 19.6 N. For the AA5182-O alloy sheets, the diagonal length of the square impressions...
was 235.7±2.4 μm; the areal fractions of the projected impressions of \( \lambda = 283, 400, \) and 566 μm were 33.8%, 16.9%, and 8.7% of the parallel part, respectively. Normally, the indentation were applied on single side (S), however, it was applied on double sides (D) under limited conditions for comparison.

Uniaxial tensile test was conducted at a constant crosshead speed of 2.5 mm/min at room temperature on an Instron-type machine. At the same time, local deformation behavior of the tensile specimen was measured by strain gauges with a gauge length GL=1, 2, or 5 mm adhered on specimen surface at the center of the parallel part.

3. Results

3.1. Change in tensile properties by indentation

Tensile properties of the initial and the indented sheets are shown in Table 1. Proof stress and tensile strength increased with an increase in magnesium content, AA5052 (Al-2.5%Mg) < AA5154 (Al-3.5%Mg) < AA5022 (Al-4.2%Mg) < AA5182 (Al-4.55%Mg). The indentation had little effect on tensile strength and total elongation. Figure 2 shows enlarged stress-strain curves of the AA5182 alloy sheet. Nominal strain \( \varepsilon \) in figure 2 was estimated from the displacement of the crosshead, i.e., tensile speed and duration. The initial sheet without impressions showed large yield elongation and serrated stress-strain curve. The yield elongation was clearly reduced by the indentation, however, it changed stress amplitude of the serrations little.

![Figure 1. Tensile specimen after indentation (\( \lambda = 800 \mu m \)) with schematic illustration of impression pattern (right figure).](image_url)

**Table 1.** Mechanical properties of specimen with/without indentation.

| Test material | \( \lambda / \mu m \) | 0.2% proof stress /MPa | UTS /MPa | Uniform elongation | Total elongation |
|---------------|----------------------|------------------------|----------|-------------------|-----------------|
| AA5182-O      | Initial 400 (S)      | 137                    | 274      | 0.265             | 0.294           |
|               | 400 (D)              | 129                    | 285      | 0.250             | 0.291           |
|               | 283 (S)              | 136                    | 276      | 0.255             | 0.293           |
| AA5052-O      | Initial 400 (S)      | 101                    | 198      | 0.249             | 0.318           |
|               | 400 (D)              | 104                    | 227      | 0.236             | 0.308           |
| AA5154-O      | Initial 400 (S)      | 104                    | 227      | 0.248             | 0.311           |
|               | 400 (S)              | 132                    | 275      | 0.267             | 0.289           |
| AA5022-O      | Initial 400 (S)      | 127                    | 277      | 0.260             | 0.280           |
3.2. Change in local strain by strain gauges

All Al-Mg alloy sheets showed serrations on stress-strain curve. It is known that not the stress but the strain increases in a stepwise manner [3, 4]. Evolution of local strain, $e^*$, measured by the strain gauges adhered on specimen surface is shown in figure 3. It is clear that local strain increases in a stepwise manner. Nominal strain $e^*$ increases more smoothly when the density of applied impressions is higher, e.g. (d) $\lambda = 283 \mu m$, especially in case of the longer gauge GL=5mm.

![Figure 2](image-url)  
**Figure 2.** Stress-strain curve of specimen with/without indentation (AA5182-O curves are shifted vertically. Nominal strain, $e$, was estimated from the displacement of crosshead on tensile test machine.

![Figure 3](image-url)  
**Figure 3.** Local strain evolution measured by the strain gauges of GL=2 and 5 mm (AA5182-O).
In figure 4, outputs of the two strain gauges are compared. One strain gauge was adhered on front surface of the specimen, while the other strain gauge was adhered on the back surface. Outputs of the two strain gauges were approximately equal so that the presence of the impressions on the adhered surface was not important. In other words, the deformation is uniform through the thickness of the specimen, while the deformation is not uniform in the tensile direction. In figure 3, gradient of stepwise strain measured by GL=2 mm was steeper than by GL=5 mm. The gradient difference can be explained by the fact that the shorter the gauge length, the shorter the duration required for deformation bands to propagate through the strain gauge.

The increase in step height of stepwise strain indicates that the ratio of (band propagation distance) / (gauge length) is higher and the deformation is more concentrated and nonuniform. To evaluate
quantitatively, average local strain increment per step, $\Delta e^*$, was calculated by dividing strain increase by the number of steps appeared in the testing time from 10s to 40s. The calculated strain increments per step $\Delta e^*$ for two gauge length (GL=2mm and 5mm) are compared in figure 5. $\Delta e^*$ decreased, i.e., the deformation became more uniform with increasing impression density. The uniformity depended on the density of impressions instead of the number, because no significant differences was observed between the single-sided (S) and the double-sided (D) specimens. For the specimens after the indentation, it was found that propagation distance of deformation bands is less than 5 mm because $\Delta e^*$ measured by GL=5 mm was smaller than by GL=2 mm. On the other hand, $\Delta e^*$ of the specimen without indentation show weak dependence on gauge length. The results suggest band propagation distance for the specimen with the indentation is shorter than the specimens without the indentation. In other words, nonuniform deformation associated with concentrated deformation bands is suppressed by the periodic indentation.

Figure 6 shows the effects of the indentation on $\Delta e^*$ for four Al-Mg alloys. The indentation
reduced $\Delta e^*$, i.e., stepwise strain evolution became smooth for all test materials. Suppressing effect by indentation does not strongly depend on Mg content, however, $\Delta e^*$ may decrease with increasing Mg content [7, 8].

4. Discussion

To observe the propagation of deformation bands, five strain gauges with GL=1 mm arranged with 2 mm interval in a loading direction were used. Adjacent three strain gauges showed same strain behavior with time lag as shown in figure 7. The behavior can be explained aforementioned discussion: propagation distance of deformation bands is less than 5 mm. Mean propagation speed of deformation bands calculated from the time interval and the distance between strain gauges was 5.9 mm/s for the specimen without the indentation, and 4.0 mm/s for the specimen with the indentation of $\lambda=566 \ \mu$m. The propagation speed in the initial sheet 5.9mm/s is closed to 6.2mm/s reported for AA5052 alloy sheets [9]. It is obvious that strain concentration occurred in units of a few millimeters as the propagation speed was about a hundred times faster than the crosshead speed of tensile test machine.

It is supposed that yield elongation decreases, and the band propagation is shortened and slowed since a large number of deformation bands are generated from the impressions. As a result, the indentation suppresses the strain concentration and the nonuniform deformation. The method using the indentation can be introduced locally without doping alloying elements and is expected to be used in sheet metal forming process. As the indentation can be applied only on single side, surface quality of the other side maintains. If the sheet was used for bodies and cups, decrease in outer surface quality by the indentation may not be a drawback.

5. Conclusion

In order to suppress the serrations on stress-strain curve, this study proposed application of periodic micro indentations on specimen surface to induce uniform deformation. Four Al-Mg alloy sheets were investigated by tensile test after lattice-pattern indentations. The following remarks were found.

1. Serrations on stress-strain curve are caused by nonuniform deformation associated with concentrated deformation bands. The nonuniform deformation is more obvious in Al-Mg alloy with increasing magnesium content. The periodic indentation suppresses serrations on stress-strain curves, while shows little effect on tensile properties.

2. High-density impressions are more effective to suppress serrations.

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References

[1] Sutoh E 1970 Strecher Strain (Sendai: The Japan Inst. of Metals and Materials)
[2] Pink E and Grinberg A 1984 Aluminum 60 687-691 764-768
[3] Curtin WA, Olmsted DL and Hector LG 2006 Nature Materials 5 875-880
[4] Nakayama Y, Nomura K and Furuta M 2006 J. Japan Inst. Light Metals 56 1 39-44
[5] Onodera R, Nonomura M, Aramaki M 2000 J. Japan Inst. Metals 64 12 1162-1171
[6] Ikeno S, Uetani Y and Tada S 1984 J. Japan Inst. Metals 48 12 1163-1167
[7] Yanagawa M and Oie S 1991 J. Japan Inst. Light Metals 41 2 119-125
[8] Kami T, Yamada H and Ogasawara N 2017 Abstracts of 132th Congress of J. Japan Inst. Light Metals 331-332
[9] Shimo K, Obata Y and Mori Y 2007 Abstracts of 40th Meeting in College of Industrial Technology, Nihon University.