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Improvement of Formability of 6xxx Aluminum Alloys Using Incremental Forming Technology

Sergey F. Golovashchenko and Al Krause

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Aluminum sheet is becoming increasingly common as an automotive body panel material. The heat-treatable aluminum alloys of the 6xxx series are widely used as an outer panel material, due to their ability to precipitation harden during the paint-bake cycle, resulting in improved dent resistance. Increasing the formability of these alloys would allow for multiple parts of less complex geometry to be combined into a single more complex part, thereby avoiding the costs associated with any subsequent joining operations. Incremental forming is a process that can improve material formability through the use of short, recovery heat treatments applied between increments of deformation. The objective of this study was to investigate the incremental forming behavior of 6111-T4 an alloy, which is often used for exterior body panel applications. Interrupted tensile testing was used to simulate the incremental forming process. The effect of different heat-treatment parameters on mechanical properties was analyzed. The heat treat regimen developed for uniaxial testing was then applied to a series of plane strain tests using a hemispherical punch, to simulate the more complex states of stress found in forming operations.

Keywords aluminum alloy, heat treatment, incremental forming, sheet metal stamping

1. Introduction

Insufficient formability can be a major issue in the manufacturing of complex parts, particularly in aluminum alloys that have less formability than steel does. One solution is to stamp less complex geometries and then join these parts through spot welding or riveting. This adds cost and increases the number of parts on a vehicle. One way to extend the formability of aluminum is to deform the sheet at an elevated temperature, which, depending on the temperature and the mechanism of material deformation, can be called warm forming (WF) or superplastic forming (SPF). Stamping at an elevated temperature can produce an issue with lubrication, but for SPF initial material cost and mechanical properties after forming may be a concern. Another approach can be to use an interim heat treatment to restore the material's ductility (Ref 1). Depending on the alloy, this procedure may require a significant period of time and a precise heat treatment schedule. Yet another approach is the subject of this work, and that is to determine the technical feasibility of partial forming, followed by fast heat treatment and then further deformation. This process may be called incremental forming (IF). The idea of retrogressive heat treatment was originally applied to production of aluminum ladders (Ref 2). Later, it was implemented at General Motors (Ref 3); a similar heat treatment approach was used to improve the quality of hemming by heat treating 6111-T4 panels between 250 and 500 °C up to 10 s and then quenching the treated region to soften it. As a result, this procedure extended the localization part of the stress-strain curve but did not affect the total elongation of 6111-T4 (Ref 4). This work investigated factors that could possibly have an effect on elongation and whether the results could be translated from deformation modes. Therefore, the alloy AA6111-T4 was chosen to represent a typical alloy for use as an exterior automotive panel with the intent of identifying a heat-treatment regimen that can restore the formability of a metal after a certain level of cold plastic deformation without penalizing other performance characteristics, and in a reasonable period of time.

Sergey Golovashchenko and **Al Krause,** Ford Research and Advanced Engineering, Manufacturing and Processes Department, 2101 Village Road, Dearborn, MI 48124. Contact e-mail: sgolovas@ford.com.

2. Experimental Approach

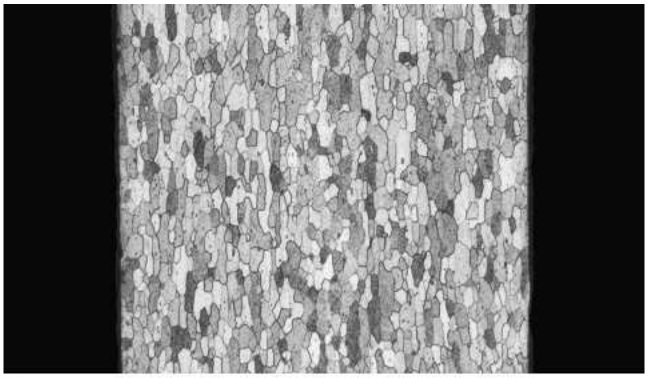
The microstructures of the AA6111-T4 (Fig. 1), both in the as-received condition and after 10% elongation, revealed a grain distribution that varied significantly in size and geometry. The larger grains were predominately elongated, whereas the smaller grains were more equiaxed. This difference in grain structure and size can result in nonuniform deformation of an alloy. To address this issue, intermediate heat treatments were performed to help relieve the residual stresses between the grains and achieve a more uniform deformation of the sheet.

The appropriate heat-treatment regimen was initially determined through tensile testing interrupted by a heat treatment. The first issue was to determine the engineering strain added during *i*-incremental steps calculated by the following equations:

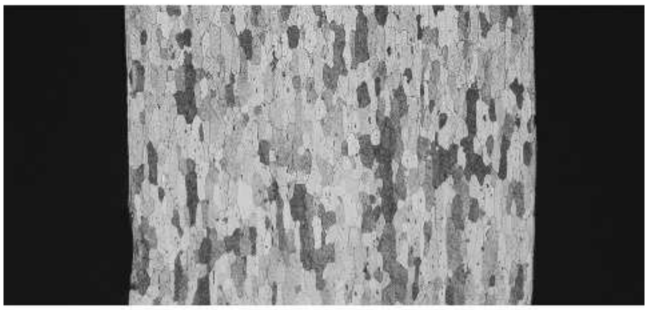
$$\varepsilon_i = \frac{(l_i - l_{i-1})}{l_{i-1}} = \frac{[l_i - l_{i-2} \times (1 + \varepsilon_{i-1})]}{[l_{i-2} \times (1 + \varepsilon_{i-1})]} \quad \text{(Eq 1)}$$

$$l_i = l_{i-2} \times (1 + \varepsilon_{i-1}) \times (1 + \varepsilon_i) \quad \text{(Eq 2)}$$

$$l_i = l_0 \times (1 + \varepsilon_i) \times (1 + \varepsilon_{i-1}) \times (1 + \varepsilon_{i-2}) \times \ldots (1 + \varepsilon_{i-m}) \times \ldots (1 + \varepsilon_2) \times (1 + \varepsilon_1) \quad \text{(Eq 3)}$$



(a)



(b)

Fig. 1 Microstructures of the AA6111-T4 sheet in as-received condition and after 10% elongation: (a) 0% prestrain (as-received) and (b) 10% prestrain

where l_i, l_{i-1}, l_{i-2} are the length of the original base l_0 after i, i–1, i–2 incremental forming steps, correspondingly.

The engineering strain accumulated through i incremental steps is:

$$\varepsilon_{1-i} = \frac{(l_i - l_0)}{l_0} = (l_i/l_0) - 1 \quad \text{(Eq 4)}$$

Substituting l_i from Eq 3 to Eq 4, the equation for accumulated engineering strain is obtained:

$$\varepsilon_{1-i} = (1 + \varepsilon_i) \times (1 + \varepsilon_{i-1}) \times (1 + \varepsilon_{i-2}) \times \ldots (1 + \varepsilon_{i-m}) \times \ldots(1 + \varepsilon_2) \times (1+ \varepsilon_1) - 1 \quad \text{(Eq 5)}$$

Equation (5) can be used in the following way: assume five incremental steps. Then,

$$l_5 = l_0 \times (1 + \varepsilon_5) \times (1 + \varepsilon_4) \times (1 + \varepsilon_3) \times (1 + \varepsilon_2) \times (1 + \varepsilon_1) \quad \text{(Eq 6)}$$

$$\varepsilon_{1-5} = (l_5 - l_0) / l_0 = (1 + \varepsilon_5) \times (1 + \varepsilon_4) \times (1 + \varepsilon_3) \times (1 + \varepsilon_2) \times (1 + \varepsilon_1) - 1 \quad \text{(Eq 7)}$$

Similarly, true strain accumulated through i incremental steps can be calculated as:

$$e_{1-i} = \ln (l_i / l_0) \quad \text{(Eq 8)}$$

$$e_{1-i} = \ln [(1 + \varepsilon_i) \times (1 + \varepsilon_{i-1}) \times (1 + \varepsilon_{i-2}) \times \ldots (1 + \varepsilon_{i-m}) \times \ldots(1 + \varepsilon_2) \times (1 + \varepsilon_1)] \quad \text{(Eq 9)}$$

Assuming that volume of the sample is constant through the testing procedure, the following equation can be written:

$$F_0 \times l_0 = F_{n-1} \times l_{n-1} \quad \text{(Eq 10)}$$

$$F_{n-1} = \frac{F_0 \times l_0}{l_{n-1}} = \frac{F_0}{(1 + \varepsilon_{1-(n-1)})} \quad \text{(Eq 11)}$$

where F_0 and l_0 are the original cross-section and the base distance for the tensile sample $\varepsilon_{1-(n-1)}$ is accumulated engineering strain from 1 to $(n - 1)$ incremental steps.

The yield stress at the beginning of n-incremental step σ_n, having $(n - 1)$ steps can be recalculated taking into account the changes in the original cross-section due to elongation of the sample as:

$$\sigma_n = \sigma_n^* \times [(1 + \varepsilon_{n-1}) \times (1 + \varepsilon_{n-2}) \times \ldots \times (1 + \varepsilon_2) \times (1 + \varepsilon_1)] \quad \text{(Eq 12)}$$

where σ_n^* is engineering stress calculated as a ratio of a tensile force to the original cross section of the sample F_0.

Factors for consideration in attempting to improve the formability of the alloy were the heat treatment temperature, time at temperature, and the amount of deformation between heat treatments. It was decided that the initial strain should reflect an adequate amount of deformation that might be observed at the first forming operation of a part, therefore it was fixed at 12%. This is enough deformation to generate a significant amount of microstructural damage but not enough to cause localized necking. The next consideration was the heat treatment temperature. The limitation on an AA6xxx alloy is that it is an age-hardenable alloy, and heat treatment temperatures that would cause age hardening would be counterproductive to increasing overall sheet deformation. The temperature selection is further complicated by the fact that the aging process can be increased by the stored energy supplied by cold work. Time, a critical factor for manufacturing, could allow for higher temperatures of heat treatment because for short durations there would be insufficient time to reach the actual furnace temperature. Therefore, a temperature in the range of 300-250 °C was chosen as a reasonable starting point, and increments of strain were initially fixed at 12%. The first series of experiments were in the middle of this range, 275 °C. Three times, i.e., 120, 60, and 30 s, were used with the results shown in Table 1. The first item of note in Table 1 is the total elongation for a soaking time of 120 s produced lower ductility than samples that were not heat treated (25% for nontreated and 23.8% for treated).

The stress at the end of a strain increment was lower than the starting stress for the next increment indicating that artificial aging was occurring, and thus, was not the desired direction. Table 1 also revealed that as the heat treatment time decreased, elongation increased, accompanied by a decrease in the starting stress compared with the previous ending stress. This indicated that some recovery was occurring, which of course was the desired result. Decreasing the heat treatment time from 60 to 30 s had little effect on ductility. Shorter time increments are desirable for stamping; therefore, the next series of experiments investigated the effect of temperature on ductility, with the holding time held constant at 30 s.

The results of varying the temperature are shown in Table 2. The average elongations for 300, 275, and 250 °C, respectively, were 29.2, 34.2, and 33.4%. The variation of 50 °C in temperature (300 to 250 °C) produced only a slight difference in

Table 1 6111 heat treat temperature 275 °C

Sample number	Time in furnace, s	Strain increment	0-12%	12-25.4%	25.4-40.5%
1	120	Yield stress	151.4	328.7	
		Stress at end	297.7	387.1	
		Final elongation	…	24.3	
2	120	Yield stress	152.8	326.7	
		Stress at end	301.3	382.7	
		Final elongation	…	24.0	
3	120	Yield stress		326.9	
		Stress at end		378.3	
		Final elongation		23.2	
4	60	Yield stress	151.4	277.1	335.2
		Stress at end	297.7	356.5	365.1
		Final elongation	…	…	30.4
5	60	Yield stress	152.8	261.6	344.4
		Stress at end	301.3	354.7	382.1
		Final elongation	…	…	32.3
6	60	Yield stress		283.0	330.6
		Stress at end		357.3	374.8
		Final elongation		…	33.0
7	30	Yield stress	151.4	286.9	328.4
		Stress at end	297.7	357.6	374.5
		Final elongation	…	…	34.8
8	30	Yield stress	152.8	288.1	326.3
		Stress at end	301.3	354.7	375.5
		Final elongation	…	…	35.6
9	30	Yield stress		291.5	333.1
		Stress at end		357.7	366.8
		Final elongation		…	32.3

Table 2 Heat treatment results 6111 for 30 s at various temperatures

Sample number	Temperature, °C	Strain increment	0-12%	12-25.4%	25.4-40.5%
1	300	Yield stress	151.4	281.9	328.3
		Stress at end	297.7	355.4	373.4
		Final elongation	…	…	33.6
2	300	Yield stress	152.8	288.6	
		Stress at end	301.3	358.1	
		Final elongation	…	23.2	
3	300	Yield stress		283	
		Stress at end		355.6	
		Final elongation		25.4	
4	300	Yield stress		283.5	324.9
		Stress at end		357.4	376.7
		Final elongation		…	34.5
5	275	Yield stress	151.4	286.9	328.4
		Stress at end	297.7	357.6	374.5
		Final elongation	…	…	34.8
6	275	Yield stress	152.8	288.1	326.3
		Stress at end	301.3	354.4	375.5
		Final elongation	…	…	35.6
7	275	Yield stress		291.5	333.1
		Stress at end		357.7	366.8
		Final elongation		…	32.3
8	250	Yield stress	151.4	292.5	337.1
		Stress at end	297.7	362.6	376.1
		Final elongation	…	…	33.3
9	250	Yield stress	152.8	288.4	332.4
		Stress at end	301.3	356.6	360.5
		Final elongation	…	…	30.8
10	250	Yield stress		295.1	331.8
		Stress at end		359.9	377.2
		Final elongation		…	35.3
11	250	Yield stress		282.1	332.4
		Stress at end		350.9	368.4
		Final elongation		…	33.7
12	250	Yield stress		286.0	334.1
		Stress at end		358.6	374.9
		Final elongation		…	33.9

Table 3 Heat treatment results 6111 for 15 s at 250 °C

Sample number	Temperature, °C	Strain increment	0-12%	12-25.4%	25.4-40.5%
1	250	Yield stress	151.4	297	346.1
		Stress at end	297.7	358.8	364.6
		Final elongation	…	…	30.5
2	250	Yield stress	152.8	301.6	344.9
		Stress at end	301.3	363.2	366.7
		Final elongation	…	…	31.7
3	250	Yield stress		296	343.6
		Stress at end		356.6	365.4
		Final elongation		…	31.3

Table 4 6111 250 °C for 30 s at 4% increments of strain after initial 12% prestrain

Number	Strain increment	0-12%	12-16.5%	16.5-21.1%	21.1-25.9%	26-31%	31-36.3%	36.3-41.7%	41.7-47.4%	47.4-53.2%
1	Yield stress	151	292	311	325	344	351	365	366	
	Stress at end	298	319	336	350	367	376	388	387	
	Final elongation	…	…	…	…	…	…	…	46.0	
2	Yield stress	153	297	306	327	342	351	363	367	364
	Stress at end	301	321	333	349	365	375	388	393	372
	Final elongation	…	…	…	…	…	…	…	48.5	
3	Yield stress		287	317	327	341	351	359		
	Stress at end		317	338	350	364	377	378		
	Final elongation	…	…	…	…	…	…	40.4		

total elongation and relatively uniform differences in the starting stress compared with the ending stress from the previous increment. Because there was not a significant difference in total elongation, the time was reduced to 15 s as a possible avenue for improvement. The results given in Table 3 indicate the time is too short for recovery because the starting stress is approximately the same as the ending stress from the previous increment. Investigation of time and temperature revealed some improvement in total elongation. The next step was to investigate the effect of the strain increments after heat treatment.

The first step of pre-straining was at the same 12% level. This level of deformation is to a certain extent representative of a drawing operation for outer body panels. This is usually the first step in the sequence of a forming operation. The deformation increment chosen was 4% followed by a heat treatment of 250 °C for 30 s. The results listed in Table 4 show a significant improvement in formability increasing to an average total elongation of 45%. The difference in the ending and starting stresses for the next increment are also significantly closer in terms of their stress value, indicating that the heat treatment removed the majority of the damage done in the deformation increments without incurring significant aging.

2.1 Dome Testing

The initial work to investigate the possibility of increasing the elongation of AA61111 was performed only in the tensile mode. However, in most forming operations there is almost always a combination of stress states. A series of plane strain tests was performed using a hemispherical punch to determine the forming limit diagram. The procedure was similar to that used in the incremental tensile tests. The initial punch travel was 19 mm, after which the samples were heat treated at 250 °C for 30 s, and then deformed another 2 mm, heat treated, and deformed another 1.5 mm. The increments were decreased because the objective was to maintain approximately 4% increments of strain with each series. The local deformation increases with increasing punch travel due to the geometry of the hemispherical punch. The sequence of punch travel was 19, 21, 22.5, 23.5, 24.1, 24.9, 25.9, 27, and 28 mm. The final elongation plane strain was approximately 39-44%. These results are in good agreement with the tensile results for both the number of steps to failure and the final fracture strain. Therefore, the combined state of stress found in most forming operations should have no significant effect for the increase in deformation found in tensile testing. Figure 2 shows the samples of AA6111-T4 bulged by the hemispherical punch in the as-received condition up to the fracture point (left), the aluminum

Table 5 Paint bake response of 6111-T4

Heat treatment and prestrain of samples	Yield strength, MPa
12% prestrain; 250 °C, 30s; 175 °C, 20 min paint bake	313.6
	311.4
	310.2
	318.1
Original material (12% prestrain), no in-house heat treatments	301.3
	300.1
	296.8
	301.3
12% prestrain 175 °C	309.1
	311.3
	311.3
	312.5

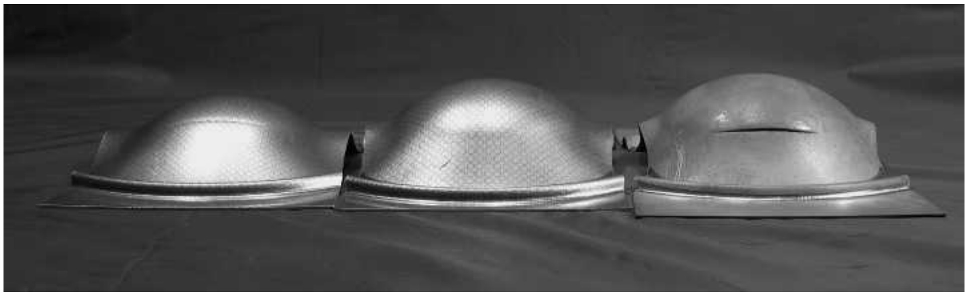


Fig. 2 Samples of AA6111-T4 bulged by the hemispherical punch in the as-received condition up to the fracture point (left), the aluminum sample bulged according to the concept of incremental forming (middle), and a low carbon steel sample (right, for comparison)

sample bulged according to the concept of incremental forming (middle), and a low carbon steel sample (right, for comparison).

2.2 Paint Bake Response

The remaining question to be answered regarded the feasibility of incremental forming for 6111-T4 in its paint-bake cycle after these intermediate heat treatments. According to the existing practice, outer body panels are subjected to heat treatment in parallel with the painting operation. The response to the paint-bake cycle is dependent upon the panel being subjected to cold work. Therefore, a series of samples were prestrained 12%, and from this group a series was heat treated at 250 °C for 30 s. These samples were then subjected to a simulated paint-bake cycle of 175 °C for 20 min, and a final batch was subjected only to the paint-bake cycle. Results in Table 5 illustrate that materials pre-strained 12% and similarly pre-strained and heat treated at 250 °C for 30 s have a very small and almost identical paint-bake response. As a result of this testing, it was concluded that incremental heat treatment did not affect the paint-bake response.

2.3 Potential Industrial Embodiment of the Technology

In high-volume production, the recommended regimen of intermediate heat treatment (250 °C, 30 s) may raise a concern because the stamping rate can be significantly reduced by this time interval. For example, in stamping automotive panels, the production rate is usually in the range of 300 parts/h, which averages to about 12 s/part. To satisfy this production rate, parts could be heat treated in groups.

Another approach for incremental forming is disclosed in (Ref 5), where electromagnetic forming and induction heat treatment are combined into a single tool—an electromagnetic coil with a field concentrator. Several coils systems can be connected to one electromagnetic forming machine, so the heat treatment and forming of several parts can be conducted in parallel, satisfying the required stamping rate.

3. Conclusions

Heat treatment of pre-strained AA6111 samples at 250 °C for 30 s provided sufficient recovery to increase elongation from 25% to approximately 45%. The state of deformation stress did not affect the results. It has been suggested that the IF process may serve as a new avenue for increasing the formability of AA6111 and as an inexpensive alternative to warm forming for 5xxx alloys.

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