

Failure predictions in warm forming of 7075-T6 aluminum structural parts

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Abstract. Today's automotive industry is increasingly adopting aluminum alloys. The main benefit of aluminum is a higher ratio of strength density compared to common steel alloys. Replacing steel with aluminum can give a weight reduction without loss of frame rigidity or crash safety. However, stamping aluminum is more difficult than steel because of its limited formability and the lack of experience with aluminum alloys for design and manufacturing requirements. Warm forming aluminum can help improve formability. Finite element analysis is a useful tool for predicting stamping failures. With accurate predictions stamping countermeasures can be made before tooling is cut and production has begun. Simulation was used to predict splits in a sidebar part formed at room and elevated temperatures. Forming limit curves were developed and used to test the formability using forming limit diagrams. Both forming limit diagrams and thinning were insufficient to predict the splits seen in the parts. This led to the use of additional fracture criteria that were successful in predicting the severity and locations of the splits.

1. Introduction

A decrease in aluminum material cost and an increased focus on automotive efficiency have led to greater use of aluminum alloys in automotive structures. In general, aluminum alloys offer a greater strength to weight ratio than steel. "Aluminum is generally 1/2 as strong as steel, but 1/3 as heavy or dense" [1]. Redesigning a steel part to be thicker and made of an aluminum alloy can provide the same rigidity and crash performance at a 33% reduction in weight. With improved part design, a weight reduction of 40-50% can be expected [1].

Forming aluminum alloys is more challenging than steel. Aluminum alloys wrinkle and springback more than steel [1] and surface quality is a greater concern because of galling and slivers of aluminum that are formed by trimming operations. Many of these manufacturing issues can be detected and counter measured using finite element analysis (FEA). FEA has become an important tool in predicting manufacturing issues at the part design stage. Thinning limits and forming limit diagrams (FLD) are the most common criteria used for predicting splits and cracks during sheet metal forming. Using a FLD requires a forming limit curve (FLC) that is obtained from material testing (Marciniak, Nakazima, Hasec, etc.) or from analytical models such as the Stuart-Keeler model. The FLC has a characteristic "V" shape when plotted on the FLD as a function of maximum and minimum strain values. If the strain path in the material remains below the FLC, then failure is not expected.

FLDs are the best tool available to predict necking failure [2]. One of the main limitations of this method is that the maximum and minimum strains can only be measured on parts after they are etched



with a pattern that can be measured manually (circle-grid) or with digital image correlation (DIC). Using thinning as a limit is not as accurate as using FLD; however, it is less expensive to acquire and thickness can be measured directly with callipers or ultrasonic equipment.

Thinning can be plotted in the same format as the FLD (figure 1). The result is a diagonal line similar to the left side of the FLD. Indeed, the left side of the FLD is very similar to a uniform thinning criterion. However, the right side of the FLD (stretching in both major and minor directions) allows additional thinning without failure. Therefore, a thinning limit overpredicts the likelihood of failure when the material is stretched in both principal directions.

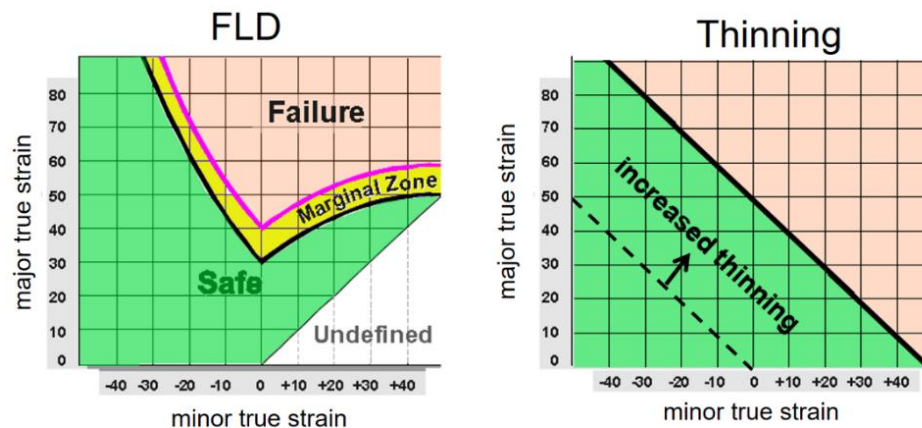


Figure 1. Comparison of FLD and thinning limit criteria.

Series 7xxx aluminum alloys are commonly used in aerospace and recently are being considered for automotive structures. This alloy category offers a high strength-to-weight ratio (see table 1). However, the material has poor formability. To overcome this, the material can be formed at elevated temperatures.

Table 1. Strength to weight ratios of common aluminum and steel alloys [1].

Class	Spec	Yield strength (MPa)	UTS (MPa)	Strength-to-weight ratio
Aluminum alloys	AA5182-O	125	270	0.9
	AA5754-O	110	220	0.7
	AA6111-T4	155	290	1.0
	AA6451-T4	110	210	0.7
	AA7075-T6	480	540	1.8
Steel grades	AKDQ	200	300	0.3
	HSLA 350	375	475	0.5
	DP 590	350	650	0.7
	DO 980	700	1050	1.2
	Press-hardened steel	1000	1500	1.7

Strength-to-weight ratio normalized to Al: UTS = 300 MPa

Press-hardened steel = hot stamped baron steel

2. Objective

The objective of this study is to characterise the material properties of 7075-T6 Aluminum at room and elevated temperatures and demonstrate increased formability at higher temperatures. An increased resistance to cracks was expected as forming temperature was increased. To show the benefit in warm forming, a part with limited formability at room temperature was used.

3. Procedure

Tensile tests were performed in the rolling direction, 45 degrees to the rolling direction and 90 degrees to the rolling direction (figure 2). The material properties obtained were: yield strength, Young's modulus, hardening curves, and R-values (Lankford coefficients). Testing was performed at room temperature (20°C), 150°C, 185°C, and 220°C. Because hardening curves have an increased strain rate sensitivity as temperature is increased, multiple strain rates (0.007/sec and 5/sec) were used for testing the temperatures above room temperature (20°C).

FLC data was obtained using Nakajima samples with the support of DIC (table 2). To determine the strains that produce necking, DIC is used to obtain the FLC. FLC testing methods that look for cracks to form or the load to drop will lead to overly conservative forming limits. FLC data was obtained at 150°C, 200°C, and 250°C.

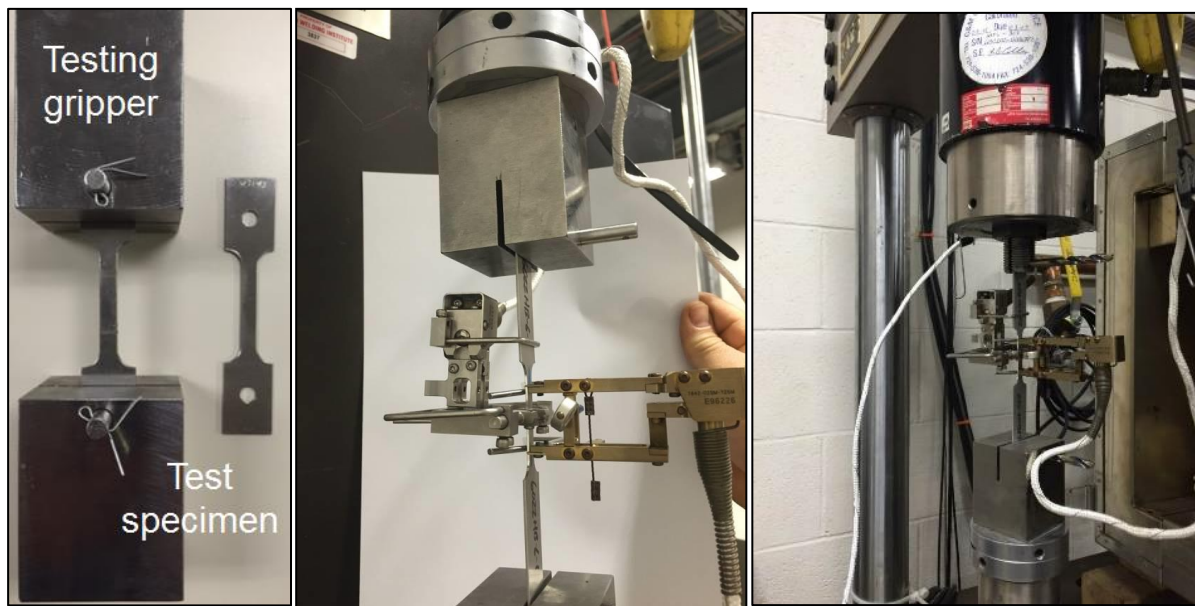


Figure 2. ASTM tensile test specimen (left), a slow rate testing fixture (middle), and a fast rate testing fixture (right) at room temperature (i.e., slow rate is 0.006 s^{-1} and fast rate is 5.5 s^{-1}).

Material tensile data and FLD results were used to create the material file. The top and bottom crash-form tooling was imported for the corresponding 1.5-mm thick sidebar part (figure 3). Initial blank dimensions and pilot pins were defined. The forming operation was simulated with an initial workpiece temperature of 20°C, 150°C, 185°C, and 220°C.

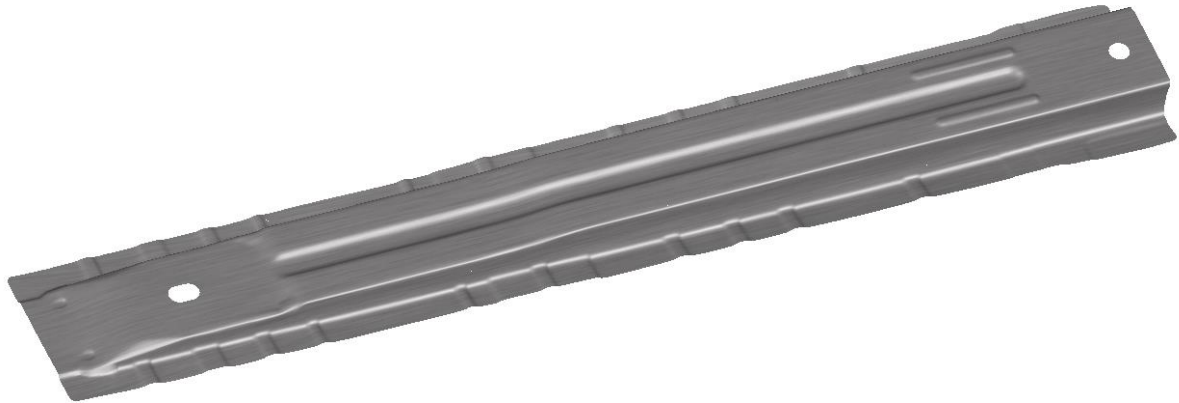


Figure 3. Sidebar part.

All the simulation results showed a good part, without split defects. To make the part less formable, radii on the bottom tool were tightened until the smallest part radii was equal to the sheet thickness. The resulting tooling change produced two marginal areas in the room temperature simulation (figure 4). Higher temperature simulations did not show any defects with the new tooling.

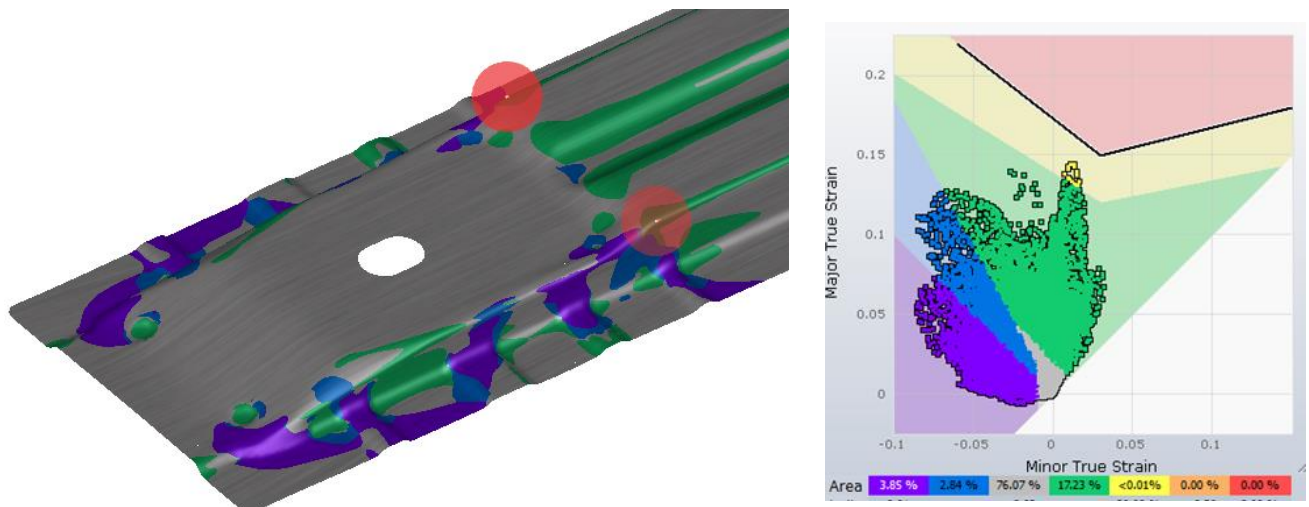


Figure 4. Sidebar simulation result at 20°C.

Tooling was cut to the dimensions used in simulation. Five blanks were run at each temperature (20°C, 150°C, 185°C, and 220°C), with and without lubricant.

4. Results

The 20°C simulation showed only a “risk” of splits. However, the real cold formed parts had large cracks (figure 5). Even though extra care was taken to obtain material properties and FLC data, the simulation had poor correlation with the real process. Correlation was poor because the failure mechanism that is predicted by FLD is not the same as what was experienced by the part. FLD predicts necking failure. Necking occurs when the sheet is over stretched. The cracks that the sheet experienced during forming were not due to necking. The fracture was the result of surface cracks that came from a high bending ratio.

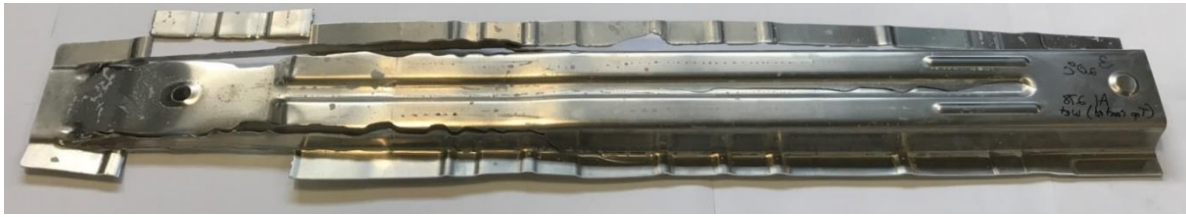


Figure 5. Cracks in the 20°C sidebar part.

Bending a material over a radius puts the material closest to the radius in compression while the far side experiences tension (figure 6). If the tensile stress is high enough, cracks will form on the surface and propagate. A material's bendability can be defined by the smallest r/t value that can be achieved by bending a sheet over smaller and smaller radii (figure 7). Aluminum is generally more susceptible to surface cracks than steel [3].

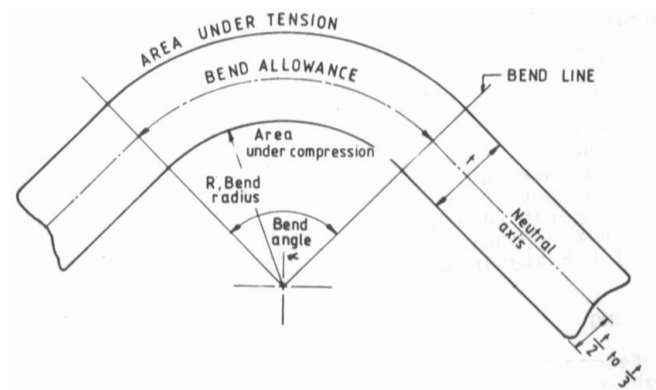


Figure 6. Stresses in a bent sheet [4].

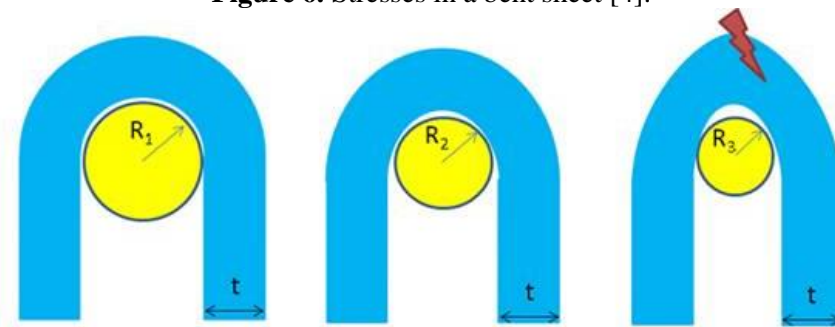


Figure 7. Illustration of bending ratio testing [3].

AutoForm utilizes a surface crack state variable for predicting bending failure mechanisms. It requires a r/t ratio or critical surface strain value. Performing the bend ratio testing was outside the scope of this work. Instead of physical testing, a series of simulations were run with various r/t ratios. Using a $r/t=2$ value in simulation correlated well with the cracked part (figure 8). This bending ratio matched the American Machine Tools Co. recommendation from their website [5]. Unfortunately, the surface crack model is only available in AutoForm for cold forming. The parts formed at 150°C saw a dramatic reduction in cracking and at 250°C, there was no cracking observed (figure 9).

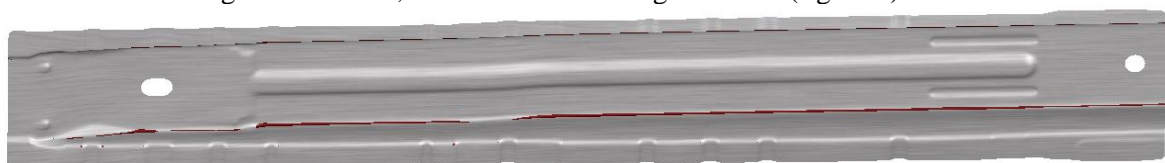


Figure 8. 20°C AutoForm simulation with edge cracking prediction.

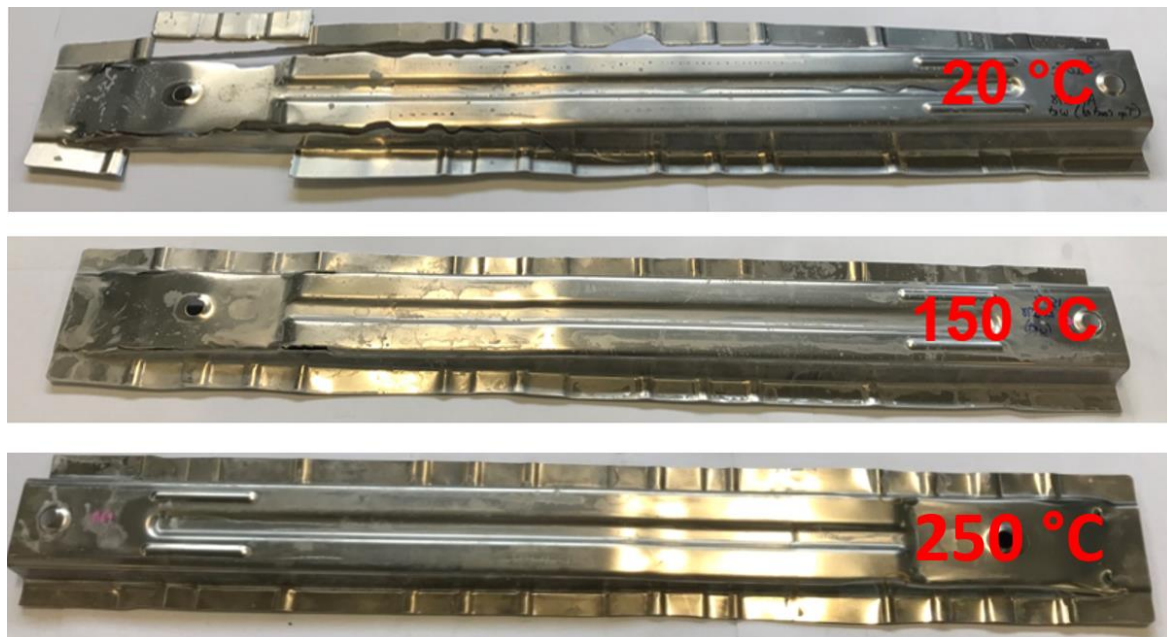


Figure 9. Parts formed at 20°C, 150°C, and 250°C.

5. Conclusions

The 7075-T6 Aluminum material properties were successfully characterised and used in AutoForm. The sidebar part was not formable at room temperature. Increasing the temperature improved formability and at 250°C, a good part was formed.

FEA has proven to be a valuable tool for predicting formability issues in sheet forming. Much work is being done to improve the forming limit approach and capture necking failure more accurately. In this case, necking was not a limiting factor. This work shows that 7xxx series aluminum is susceptible to bending surface cracks. The bending ratio of the material should be known at the design stage and sufficiently large tooling/part radii should be used to prevent surface cracks in the part. Using a r/t ratio greater than 2 is recommended for 7075-T6 alloys.

More work is needed to develop surface crack models. The simple bending ratio is not always sufficient to catch surface cracks. It is possible to have a design with a relatively large r/t cause surface cracks. Strain-based testing with DIC is likely a good step forward. Beyond that, high-temperature surface crack models must be developed. Without accurate surface crack models, conservative r/t ratios must be used or surprise cracks may show up in production.

Acknowledgments

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