LEVELING AUTOMOTIVE ALUMINUM SHEET

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1 Introduction

The adoption of aluminum auto body sheet is a standard practice in automotive manufacturing, driven by the industry's pursuit of lightweight vehicle designs and improved fuel efficiency. Recent market analyses, such as the April 2023 Ducker Carlisle report, project that the average aluminum rolled product content in North American vehicles will increase from 60kg in 2022 to over 67kg by 2030. This trend reflects not only the growing demand for aluminum but also the expansion of manufacturing infrastructure and expertise across the automotive sector.

In the production workflow, aluminum coils fabricated at rolling mills serve as the starting point for automotive original equipment manufacturers (OEMs). These coils must be converted into flat blanks before entering forming dies—a process that requires precise mechanical leveling. Leveling, performed by machines known as "levelers" or "straighteners," involves passing the sheet through a series of rollers to eliminate coil curl and achieve the required flatness. A schematic of a '5 over 6' leveler is shown below (Figure 1). (Please note that it is not to scale). While essential for downstream forming operations, this process introduces repeated bending and unbending, which can alter the sheet's mechanical properties.

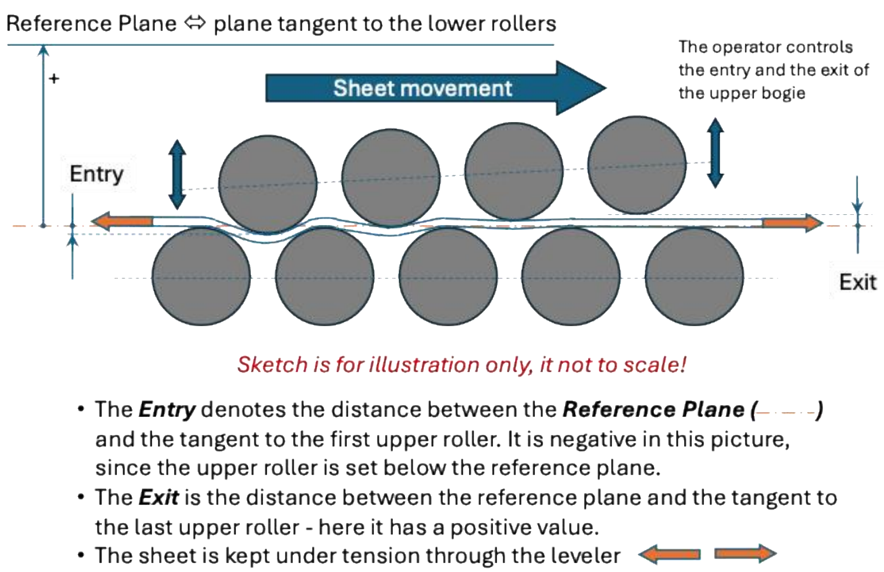

Figure 1: Schematic of a leveler, sheet moving from left to right.

Despite the widespread use of leveling in high-volume automotive applications, there is limited quantitative data on how this process affects the mechanical properties of outer quality aluminum auto body sheet. Addressing this knowledge gap, the Aluminum Transportation Group (ATG) of the Aluminum Association, representing the companies that make 70% of the aluminum and aluminum products shipped in North America, sponsored the present study. The objective is to systematically evaluate the changes in mechanical properties resulting from typical blanking and leveling operations, providing actionable insights for material specification and process optimization in automotive manufacturing.

2 Study

The study involved 15 identical 6xxx coils, rolled to a nominal thickness of 1.1mm, with a width of 1,800mm. The size of the coil ranged from under 6,000kg to 12,500kg, with an average mass of 11,000kg. They were all produced within the same week and represented typical 6xxx outer quality auto body sheet. Samples were captured on the blanking day before and after the leveler to quantify its impact on the mechanical properties of each coil.

2.1 Study setup

Three sets of five randomly selected coils were shipped to three established processors, who were asked to process them on two different lines. The purchase order specified rectangular blanks 1,800 wide x 1,600mm, processed to outer quality standards according to the normal setup for each line. Blanking speeds ranged from 25 to 31 pieces per minute, based on each line's capabilities. The blank flatness was evaluated regularly to confirm conformance to quality standards, and the leveler settings were adjusted if necessary.

Table 1 presents their tensile properties in the transverse direction just prior to blanking, each value representing an average of five repeats.

Yield Strength [MPa]	Tensile Strength [MPa]	Uniform Elongation [%]	Ultimate Elongation [%]	n-value (between 10 & 20%)	r-value (at 10%)
121.0	222.3	20.4	22.3	0.223	0.58
134.1	241.5	21.7	25.1	0.234	0.53
121.6	222.3	19.7	20.9	0.231	0.53
138.4	244.9	21.1	23.7	0.231	0.53
138.6	246.8	21.2	23.6	0.230	0.52
123.4	228.1	21.7	24.0	0.233	0.59
134.9	240.0	19.4	20.2	0.227	0.54
128.7	230.4	20.1	22.0	0.226	0.57
133.2	237.3	19.9	20.5	0.228	0.55

133.8	238.9	19.9	21.7	0.220	0.52
128.7	230.1	19.6	21.4	0.222	0.60
128.9	231.5	19.9	21.9	0.228	0.56
129.8	234.3	21.0	22.0	(*)	0.54
130.3	235.2	19.8	21.2	0.232	0.53
135.6	241.0	21.1	23.1	0.229	0.46

Table 1: Pre-leveling tensile properties of the coils at age six months.

(*) There was an issue with the tensile testing in the T-direction of the pre-blanking sample for this coil, and no valid n-value was obtained.

All the coils were produced between September 23 and October 1, 2024, and blanked between January and February 2025. The tensile testing was completed by the end of March 2025.

Samples were gathered at the head of each coil, before the leveler unit. Another set of samples were gathered from the first satisfactory blank, and the processing parameters recorded. If a process adjustment became necessary, new samples were gathered after the adjustment, and the new processing parameters recorded.

All the tensile testing was conducted in the same lab. Given that the testing covered all three directions and required a minimum of five repeats, the test matrix was substantial:

(15 coils) x (3 directions) x (minimum of 2 conditions) x (5 repeats) ó minimum of 450 tensile tests. Such an extensive test load would take enough time that natural ageing differences between early and late tests might become a concern. To mitigate the issue, the samples were selectively frozen to halt natural ageing, ensuring all samples had the same apparent age at the time of the tensile testing, either 182 or 183 days.

2.2 Evaluation criteria

All practitioners are aware that physical testing is inherently noisy, hence the requirement that tensile testing include repeats, and that any comparison is made on the average of the repeats.

The question posed by our study appears simple: "How much does leveling thin gage aluminum auto body sheet affect its properties?" The answer requires us to compare the potential effect of the leveler versus the inherent noise of the testing itself. It is therefore best approached with a statistical understanding. As shown below, there are at least two ways of approaching the problem.

The first and traditional way is to compare the "before" and "after" sets of tensile tests to determine if they can be considered sufficiently different by testing the "null" hypothesis.

The second approach is to compute the capabilities of the tensile test, then compute the "testing significant difference" at a given confidence interval.

The two methodologies are compared below.

2.3 Deciding on a methodology

The two methodologies yield different results; all tables reflect the differences between the average values of the samples "before" and "after" the leveler. Table 2 shows the unfiltered results:

Coil ID	d_YS_0 2.3 [MPa]	d_TS_0 2.8 [MPa]	d_YS_45 2.3 [MPa]	d_TS_45 2.7 [MPa]	d_YS_90 2.3 [MPa]	d_TS_90 2.7 [MPa]
F	0.68	-0.33	0.28	-0.47	-0.13	0.41
O	3.52	4.31	1.30	2.07	1.21	3.26
G	2.04	2.25	1.93	2.79	1.46	1.86
G'	6.40	7.61	3.85	5.03	4.14	5.20
N	3.66	6.71	1.10	-0.09	-1.00	-2.59
D	0.99	1.93	4.17	4.79	3.72	3.56
L	3.27	4.69	2.80	4.73	-0.15	-1.76
E	1.56	0.99	4.51	2.23	4.24	4.76
B	0.82	-0.77	2.80	1.33	1.64	-0.44
I	3.50	8.24	5.24	5.50	8.04	9.33
A	6.28	8.76	3.83	6.38	-0.70	-1.52
J	7.52	9.67	2.06	2.69	-1.23	-0.30
C	8.96	13.48	0.13	-0.64	0.96	0.45
M	2.23	1.34	3.77	3.30	2.91	1.08
H	2.40	0.94	1.62	-0.26	3.22	1.51
K	3.36	2.28	3.77	3.22	2.86	3.42

Table 2: Differences between "before" and "after" the leveler (unfiltered results).

Coil ID	d_YS_0 2.3 [MPa]	d_TS_0 2.8 [MPa]	d_YS_45 2.3 [MPa]	d_TS_45 2.7 [MPa]	d_YS_90 2.3 [MPa]	d_TS_90 2.7 [MPa]
F						
O	3.52					
G	2.04	2.25	1.93	2.79	1.46	1.86
G'	6.40	7.61	3.85	5.03	4.14	5.20
N	3.66	6.71			-1.00	-2.59
D	0.99	1.93	4.17	4.79	3.72	3.56
L	3.27	4.69	2.80	4.73		
E						
B			2.80		1.64	
I	3.50	8.24	5.24		8.04	9.33
A	6.28	8.76	3.83	6.38		
J	7.52	9.67	2.06	2.69		
C	8.96	13.48				
M	2.23	1.34	3.77	3.30		
H	2.40				3.22	
K			3.77	3.22		3.42
Averages						
Effect:	4.23	6.47	3.42	4.12	3.03	3.46
No Effect:	1.61	1.24	1.49	1.21	1.11	0.75

Table 3: Results filtered using the "null" hypothesis for individual before/after pairs.

Filtering the results with the "null" hypothesis identifies four coils with no apparent changes in the rolling direction (coils F, E, B, and K) highlighted in yellow in Table 4), but a closer look at Table 2 reveals five flagged coils with smaller differences in the rolling direction than the unflagged coil K. (Table 4)

Coil ID	d_YS_0 2.3 [MPa]
F	0.68
O	3.52
G	2.04
G'	6.40
N	3.66
D	0.99
L	3.27
E	1.56
B	0.82
I	3.50
A	6.28
J	7.52
C	8.96
M	2.23
H	2.40
K	3.36

Table 4: Four unflagged coils (in yellow) and five flagged coils (in green) with smaller differences than coil K.

Notably, coil D is flagged despite having one of the smallest differences. The explanation is that some samples experienced noisier testing than others, requiring a larger difference between the pre- and post-samples before a leveling effect can be confirmed. Therefore, individually testing the "null' hypothesis between "before" and "after" samples does not provide a repeatable answer when comparing multiple coils. More importantly, it does not lead to a specific value that could be used for a specification.

Coil ID	d_YS_0 2.3 [MPa]	d_TS_0 2.8 [MPa]	d_YS_45 2.3 [MPa]	d_TS_45 2.7 [MPa]	d_YS_90 2.3 [MPa]	d_TS_90 2.7 [MPa]
F	0.68	-0.33	0.28	-0.47	-0.13	0.41
O	3.52	4.31	1.30	2.07	1.21	3.26
G	2.04	2.25	1.93	2.79	1.46	1.86
G'	6.40	7.61	3.85	5.03	4.14	5.20
N	3.66	6.71	1.10	-0.09	-1.00	-2.59
D	0.99	1.93	4.17	4.79	3.72	3.56
L	3.27	4.69	2.80	4.73	-0.15	-1.76
E	1.56	0.99	4.51	2.23	4.24	4.76
B	0.82	-0.77	2.80	1.33	1.64	-0.44
I	3.50	8.24	5.24	5.50	8.04	9.33
A	6.28	8.76	3.83	6.38	-0.70	-1.52
J	7.52	9.67	2.06	2.69	-1.23	-0.30
C	8.96	13.48	0.13	-0.64	0.96	0.45
M	2.23	1.34	3.77	3.30	2.91	1.08
H	2.40	0.94	1.62	-0.26	3.22	1.51
K	3.36	2.28	3.77	3.22	2.86	3.42

Table 5: Highlighted values are larger than the "testing significant difference."

Filtering the results using the "testing statistically significant difference" is shown in Table 5, in which highlighted values exceed the significant difference (second line in the column header).

We can compare the two methods side by side:

a) Significant Difference method

Coil ID	d_YS_0 2.3 [MPa]	d_TS_0 2.8 [MPa]	d_YS_45 2.3 [MPa]	d_TS_45 2.7 [MPa]	d_YS_90 2.3 [MPa]	d_TS_90 2.7 [MPa]
F	0.68	-0.33	0.28	-0.47	-0.13	0.41
O	3.52	4.31	1.30	2.07	1.21	3.26
G	2.04	2.25	1.93	2.79	1.46	1.86
G'	6.40	7.61	3.85	5.03	4.14	5.20
N	3.66	6.71	1.10	-0.09	-1.00	-2.59
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L	3.27	4.69	2.80	4.73	-0.15	-1.76
E	1.56	0.99	4.51	2.23	4.24	4.76
B	0.82	-0.77	2.80	1.33	1.64	-0.44
I	3.50	8.24	5.24	5.50	8.04	9.33
A	6.28	8.76	3.83	6.38	-0.70	-1.52
J	7.52	9.67	2.06	2.69	-1.23	-0.30
C	8.96	13.48	0.13	-0.64	0.96	0.45
M	2.23	1.34	3.77	3.30	2.91	1.08
H	2.40	0.94	1.62	-0.26	3.22	1.51
K	3.36	2.28	3.77	3.22	2.86	3.42

b) "Null" hypothesis testing of pairs

Coil ID	d_YS_0 2.3 [MPa]	d_TS_0 2.8 [MPa]	d_YS_45 2.3 [MPa]	d_TS_45 2.7 [MPa]	d_YS_90 2.3 [MPa]	d_TS_90 2.7 [MPa]
F						
O	3.52					
G	2.04	2.25	1.93	2.79	1.46	1.86
G'	6.40	7.61	3.85	5.03	4.14	5.20
N	3.66	6.71			-1.00	-2.59
D	0.99	1.93	4.17	4.79	3.72	3.56
L	3.27	4.69	2.80	4.73		
E						
B			2.80		1.64	
I	3.50	8.24	5.24		8.04	9.33
A	6.28	8.76	3.83	6.38		
J	7.52	9.67	2.06	2.69		
C	8.96	13.48				
M	2.23	1.34	3.77	3.30		
H	2.40				3.22	
K			3.77	3.22		3.42

Figure 2: Comparing the two methodologies.

The individual tests highlight 14 values that fall below the testing significant difference (cells highlighted in red in the Significant Difference table), while they failed to recognize nine values that would have exceeded the testing significant difference (red highlighted cells without a number in the individual tests table).

For all the above reasons, we selected the second methodology for the rest of the analysis, using the testing significant difference approach.

3 Results & Discussion

As discussed in the previous section, we analyzed the results using the concept of the Significant Difference. We will first present the average results, then show the effect of each individual line.

3.1 Average hardening effect across the six lines

As one would expect, on average, the levelers, and hence blanking, had a hardening effect, increasing the Yield Strength (YS) and the Tensile Strength (TS) of the coils in the rolling direction. The effect in the diagonal and transverse directions was less pronounced, increasing the YS but with only a marginal increase in TS.

	Yield Strength [MPa]			Tensile Strength [MPa]		
	Rolling Direction	Diagonal	Transverse	Rolling Direction	Diagonal	Transverse

95%CI Significant Threshold	2.3	2.3	2.3	2.8	2.7	2.7
Average Change	**3.57**	**2.70**	1.95	**4.51**	2.66	1.76
Median Change	**3.32**	**2.80**	1.55	**3.29**	**2.74**	1.30

Table 6: Strength hardening effect.

It did not have a significant effect on either the n-value or the r-value:

	n-value			r-value		
	Rolling Direction	Diagonal	Transverse	Rolling Direction	Diagonal	Transverse
95%CI Significant Threshold	-0.005	-0.005	-0.005	-0.07	-0.04	-0.05
Average Change	-0.001	-0.001	-0.001	0.01	0.00	0.01
Median Change	-0.001	-0.001	-0.002	0.02	0.00	0.00

Table 7: Leveling effect on the n- and r -values.

Nor did it influence the elongations:

	Uniform Elongation [%]			Total Elongation [%]		
	Rolling Direction	Diagonal	Transverse	Rolling Direction	Diagonal	Transverse
95%CI Significant Threshold	-1.0	-1.0	-0.9	-1.9	-1.9	-1.8
Average Change	-0.5	-0.1	0.2	-0.4	-0.1	0.5
Median Change	-0.5	-0.2	0.3	-0.4	-0.2	0.7

Table 8: Leveling effect on elongations.

On average, we can see that the leveling affected mostly the strength of the sheet but not the other properties. The effect was most pronounced in the rolling direction, with a minor effect in the diagonal.

3.2 Influence of the individual blanking line

The study entailed six different lines, each with its own characteristics and setup. As described in Appendix B, we use a single metric describing each leveler and its settings. Our metric 'W' keeps track of the tension and compression events at the top and bottom surface of the sheet for each setup. 'W' increases with a deeper penetration, the number of bend/unbend events, and is inversely proportional to the rollers' diameter.

Table 9 presents each line and its associated coefficient 'W'. Line 1 is the only line a coil required a mid-run setting change, the line-coil pair identified as 1-G then 1-G'. Line 1 and line 5 are sister lines, using identical initial settings for each run.

Randomized line ID	Randomized Coil ID	Normalized leveler settings
1	F	0.536
1	O	0.536
1	G	0.536
1	G'	0.637
2	N	0.064
2	D	0.076
2	L	0.064
3	E	0.306
3	B	0.313
3	I	0.319
6	A	0.060
6	J	0.052
5	C	0.536
5	M	0.536
4	H	0.190
4	K	0.190

Table 9: Normalized leveler settings ('W' coefficient) and pairing of the line and coil.

Figure 3 shows the strength changes in the rolling direction for each of the line-coil pairs and their leveler:

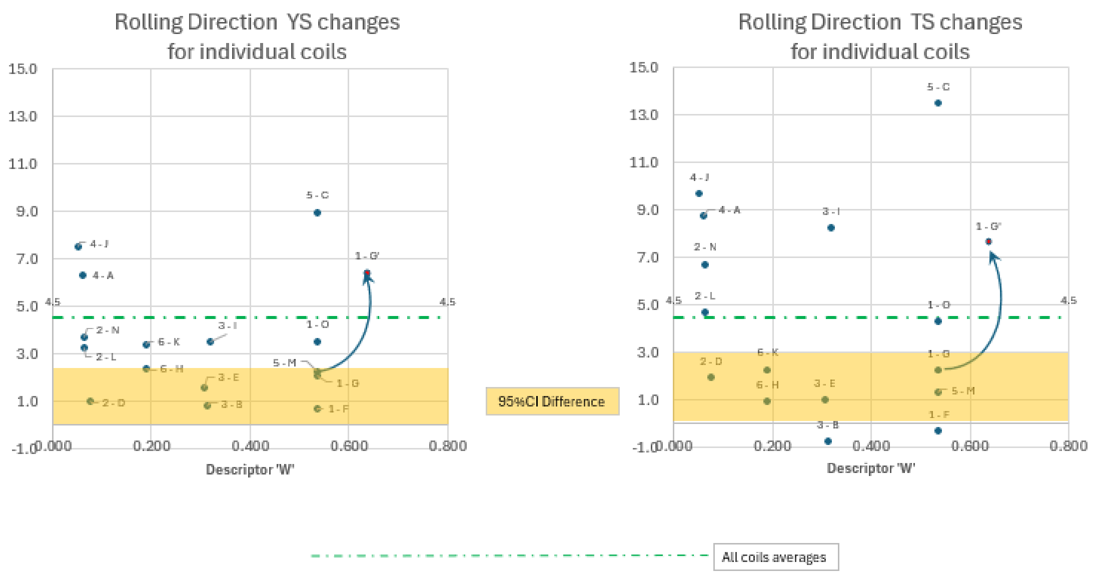

Figure 3: Rolling Direction changes (digits 1 to 6 represent the line used, each letter represents a particular coil).

Coil 1-G required a setup change in the middle of the run to keep the flatness within specifications, causing the jump to the point marked 1-G’. The most unexpected result is the range of effects, even with a stable setup. 1-F, 1-G and 5-M did not exhibit significant changes during processing, unlike coils 5-C and 1-O.

Table 10 looks at the changes from a 95%CI significant difference perspective. It covers three directions and the six major mechanical properties. The value of the significant change confidence interval is announced at the head of each column (0 ó rolling direction, 45 ó diagonal and 90 ó transverse).

Line ID	Coil ID	Labels	d_YS_0 2.3 [MPa]	d_TS_0 2.8 [MPa]	d_YS_45 2.3 [MPa]	d_TS_45 2.7 [MPa]	d_YS_90 2.3 [MPa]	d_TS_90 2.7 [MPa]	d_UE%_0 -1.0	d_TE%_0 -1.9	d_UE%_45 -1.01	d_TE%_45 -1.91	d_UE%_90 -0.93	d_TE%_90 -1.76	d_n_0 -0.005	d_r_0 -0.066	d_n_45 -0.005	d_r_45 -0.042	d_n_90 -0.005	d_r_90 -0.052
1	F	1 - F	0.68	-0.33	0.28	-0.47	-0.13	0.41	-0.04	0.22	1.10	1.67	1.58	3.90	-0.004	0.01	-0.001	0.00	-0.004	-0.01
1	O	1 - O	3.52	4.31	1.30	2.07	1.21	3.26	-0.40	-0.41	-0.93	-2.09	-2.25	-3.72	-0.001	0.04	0.001	-0.04		-0.05
1	G	1 - G	2.04	2.25	1.93	2.79	1.46	1.86	-0.64	0.67	-0.52	-1.11	0.25	1.17	-0.001	0.02	0.000	0.01	-0.001	0.00
1	G'	1 - G'	6.40	7.61	3.85	5.03	4.14	5.20	-0.05	2.04	-1.27	-2.86	-0.02	1.69	-0.001	0.00	0.000	0.00	0.000	-0.02
2	N	2 - N	3.66	6.71	1.10	-0.09	-1.00	-2.59	-1.03	-1.80	-2.48	-4.61	-1.17	-1.44	0.001	0.00	-0.003	-0.01	-0.003	0.04
2	D	2 - D	0.99	1.93	4.17	4.79	3.72	3.56	-0.29	-0.51	-0.54	-0.51	-0.91	-1.43	0.000	0.00	0.002	-0.05	-0.010	0.02
2	L	2 - L	3.27	4.69	2.80	4.73	-0.15	-1.76	-0.60	-0.48	1.20	2.55	-1.76	-2.20	0.000	0.04	0.002	-0.02	-0.003	-0.04
3	E	3 - E	1.56	0.99	4.51	2.23	4.24	4.76	0.59	0.88	0.91	1.69	0.26	0.56	0.000	-0.09	-0.001	-0.05	0.006	-0.01
3	B	3 - B	0.82	-0.77	2.80	1.33	1.64	-0.44	-0.88	-1.59	-0.34	-0.23	-0.28	-0.29	-0.004	0.02	-0.003	0.03	-0.004	0.03
3	I	3 - I	3.50	8.24	5.24	5.50	8.04	9.33	-1.62	-4.42	1.30	2.93	0.73	1.86	0.003	-0.02	-0.003	0.01	-0.005	0.00
4	A	4 - A	6.28	8.76	3.83	6.38	-0.70	-1.52	-0.83	-1.28	-1.06	-2.05	-0.11	0.00	-0.001	-0.04	0.003	-0.02	-0.002	0.02
4	J	4 - J	7.52	9.67	2.06	2.69	-1.23	-0.30	-0.88	-1.04	0.52	1.44	0.84	1.58	-0.002	0.06	-0.004	0.03	0.004	0.09
5	C	5 - C	8.96	13.48	0.13	-0.64	0.96	0.45	0.51	1.51	0.07	-0.26	0.26	0.81	0.001	0.02	-0.002	0.02	-0.002	0.02
5	M	5 - M	2.23	1.34	3.77	3.30	2.91	1.08	-0.96	-1.10	-0.58	-0.07	0.53	0.59	-0.002	0.00	-0.003	0.03		0.00
6	H	6 - H	2.40	0.94	1.62	-0.26	3.22	1.51	0.09	0.25	-0.13	0.88	1.70	3.10	-0.002	0.04	-0.004	0.04	0.007	0.04
6	K	6 - K	3.36	2.28	3.77	3.22	2.86	3.42	-0.25	0.12	1.13	1.72	1.42	2.29	-0.003	0.03	-0.002	-0.05	0.003	-0.02

Table 10: Individual effects by line and coil. All three directions, highlighted numbers mean a significant change, yellow ó drop, greenó improvement.

1) No lines left the material properties unaffected, although line 1 seemed the most benign: It had no effect on coil F, minor effect on TS_45 of coil G, and had a moderate effect on coil O. Yet, a small change in setup to accommodate an apparent change in the coil resulted in a significant hardening change (coil 1-G to 1-G’).

2) Apparent “sister lines” running with the same settings could produce significantly different results (see lines 1 and 5).
3) On any given line, different coils yielded different results (see coils C and M on line 5).
4) Hardening was generally felt in all three directions: it was significant for 10 out of 15 coils in the rolling direction, then 9 and 7 out of 15 for the diagonal and transverse directions, respectively.
5) Coils with no effect on the rolling direction did show significant changes in the other directions (coils B, D, E and M).
6) n-values in the rolling and diagonal directions do not appear to have been significantly affected.
7) Both coils processed on line 4 exhibited significant hardening, but mostly in the rolling direction.
8) 3 coils (coils F, H and K) experienced significant improvement in both uniform (UE%) and total elongations (TE%) in the transverse direction on line 1 and 6 respectively.

On closer analysis, we can observe the following:

Blanking effects on sheet properties (out of 16 readings)		Direction		
		0	45	90
YS	Worsened	10	9	7
	Improved			
TS	Worsened	9	8	6
	Improved			
UE%	Worsened	2	3	3
	Improved		4	3
TE%	Worsened	1	4	2
	Improved	1	2	4
n-value	Worsened			1
	Improved			2
r-value	Worsened	1	3	1
	Improved			1

Table 11: General blanking effects.

4.0 Conclusions

The focus of the study was to quantify the changes in mechanical properties that an automotive customer might expect from a typical blanking process for aluminum outer quality auto body sheet. The intent was to observe the current state of the blanking process without special intervention from either the customer or the mill.

While analyzing the results, we realized we were given a unique opportunity to improve our understanding of the tensile testing as well. We therefore summarized two sets of conclusions: First, the answers to our original question, and second, the learning regarding tensile testing.

4.1 Regarding the blanking process

All conclusions are based on a 95% confidence interval of a significant difference. Blanking involves leveling a coil and it does affect its mechanical properties, but not in a straightforward manner.

1) The study highlights the need for the industry to consider the variations in mechanical properties caused by blanking/leveling into the material specifications and the stamping process development (including simulation) to ensure robust production.
2) Leveling a coil affects the mechanical properties of aluminum auto body sheet, albeit in ways that are not always obvious. In the rolling direction, we observed statistically significant changes affecting the Yield and Tensile Strengths:
    a. The maximum recorded changes for the YS and TS were 9.0MPa and 13.5MPa, respectively, with three coils averaging 7.6MPa in YS changes.
    b. The maximum effect happened on a line on which the other coil changed very little and whose sister line was the gentlest.
    c. The elongations and the ‘n’ and ‘r’ values were not meaningfully affected by the leveling (see table below).
3) While smaller, the average effects on strength in the other directions were not negligible.
4) The changes in mechanical properties did not appear to be solely tied to the lines themselves. Identical setups affected different coils in statistically different ways.
5) Numerically, our 15 coils blanked on six different lines yielded the following changes in mechanical properties (the highlighted values exceed the threshold for a change to be deemed statistically significant).

Change “After” – “Before” [MPa]	dYS_0	dTS_0	dYS_45	dTS_45	dYS_90	dTS_90
Average	3.6	4.5	2.7	2.7	1.9	1.8
Median	3.3	3.3	2.8	2.7	1.6	1.3
Standard Deviation	2.5	4.1	1.5	2.3	2.5	3.1
Max	9.0	13.5	5.2	6.4	8.0	9.3
Min	0.7	-0.8	0.1	-0.6	-1.2	-2.6

Change “After” – “Before”	UE%_0	TE%_0	UE%_45	TE%_45	UE%_90	TE%_90
Average	-0.5%	-0.4%	-0.1%	-0.1%	0.1%	0.5%
Median	-0.5%	-0.4%	-0.2%	-0.2%	0.3%	0.7%
Standard Deviation	0.59%	1.5%	1.1%	2.1%	1.1%	2.0%
Max	0.6%	2.0%	1.3%	2.9%	1.7%	3.9%
Min	-1.6%	-4.4%	-2.5%	-4.6%	-2.3	-3.7%

Change “After” – “Before”	dn_0	dr_0	dn_45	dr_45	dn_90	dr_90
Average	-0.001	0.01	-0.001	0.0	-0.001	0.01
Median	-0.001	0.02	-0.001	0.0	-0.002	0.0
Standard Deviation	0.002	0.04	0.002	0.03	0.005	0.04
Max	0.003	0.06	0.003	0.04	0.007	0.09
Min	-0.004	-0.09	-0.004	-0.05	-0.01	-0.05

6) Based on one observation, even a small setup adjustment had a statistically significant impact, causing a rolling direction YS increase to grow from 2MPa (not statistically significant) to 6MPa (statistically significant).

4.2 Statistical understanding of the tensile test

We are all aware that tensile testing exhibits a certain amount of noise. Two tensile tests with different results do not necessarily imply a real difference. Averaging multiple repeats helps, but even then, testing noise should be considered.

Our study involved comparing 48 pairs of tensile test results, based on more than 600 individual tensile tests, all performed by a single lab. This gave us a solid statistical basis to quantify the inherent noise of testing thin gage aluminum auto body sheet.

We summarized the results below with details in Appendix A.

1) Because it involves comparing pairs of small sample averages, the case-by-case testing of the “null” hypothesis can yield surprising conclusions, with one case showing 1MPa as meaningful change, while another informing us that a 3.3MPa difference is not. Such cases highlight the difficulties in comparing small samples averages.
2) The concept of a statistically Significant Difference over a 95% Confidence Interval appears better suited to deciding if a change in mechanical properties is real than a traditional case-by-case testing of the null hypothesis.
   a. After normalization, our tensile testing of thin gage 6xxx aluminum auto body sheet yielded the following information:

	YS	TS	UE%	TE%	n-value	r-value
Standard Deviation	1.38%	0.92%	3.71%	6.38%	1.75%	7.67%

These results confirm that the total elongation (TE%) and the r-value are the noisiest results of the tensile test.

   b. The associated normalized Significant Differences for two sets of five-test averages were:

	YS	TS	UE%	TE%	n-value	r-value
95%CI Normalized Significant Difference	1.71%	1.14%	4.59%	7.91%	2.17%	9.50%

The above values highlight the difference required to conclusively state that blanking affected a specific mechanical property of a coil.

These results could be used to start the discussion around specific requirements for blanks versus coils.

Numerically, for the 6xxx outer quality coils used in the study, after ageing six months:

Coils in our Study	YS [MPa]	TS [MPa]	UE%	TE%	n-value	r-value

95%CI Significant Difference	2.3	2.8	-1%	-1.9%	-0.005	-0.05

We note the size of a significant change for the n- and r-values.

4.3 Final thoughts

Overall, these results support the continued refinement of material specifications and process controls in automotive manufacturing and provide a foundation for future research into the effects of blanking and leveling on advanced aluminum alloys. The insights gained here will help engineers, designers and decision-makers ensure robust, high-quality production in an evolving industry landscape.

Appendix A – Two different statistical methodologies

A-1 Comparing individual sets with the "null" hypothesis

As noted earlier, we tested each material sample with five or six repeats, enough to derive a small sample average. The conservative approach is to use a two-tail test, which we outline below.

For each set identified by 'i' =1 or 2, the testing yielded samples 'j' identified by 'j'= 1 to n_i, where n_i = number of tests in sample 'i'.

We can calculate the average $\overline{x_i}$ of the individual measurements x_j, where 'j' is the repeat identifier for the tests in each set:

$$\overline{x_i} = \sum_{1}^{n_i} x_j / n_i$$

From there, we compute the sum of the square differences for each sample:

$$SS_i = \sum_{1}^{n_i} \left(x_j - \overline{x_i}\right)^2$$

At this stage, we have two possible cases:

A.1.1 Comparing two sets with an equal number of tests.

We compute the degrees of freedom:

$$df = (n_1 - 1) + (n_2 - 1)$$

Because we have an equal number of tests for each sample, we can compute the pooled variance:

$$s_p{}^2 = (SS_1 + SS_2)/df$$

Then we compute the test statistic 't':

$$t = (\overline{x_1} - \overline{x_2}) / \sqrt{\left(\frac{s_p{}^2}{n_1} + \frac{s_p{}^2}{n_2}\right)}$$

A.1.2 Comparing two sets with an unequal number of tests.

Because we have samples with an unequal number of tests, we compute the individual variances:

Each variance ‘i’:

$$s_i^{\,2} = SS_i/(n_i - 1)$$

Because of the unequal number of tests, we can compute the degrees of freedom by using Welch’s approximation, rounded down to the nearest integer:

$$df = \left(\frac{s_1^{\,2}}{n_1} + \frac{s_2^{\,2}}{n_2}\right)^2 / \left[\frac{\left(\frac{s_1^{\,2}}{n_1}\right)^2}{(n_1 - 1)} + \frac{\left(\frac{s_2^{\,2}}{n_2}\right)^2}{(n_2 - 1)}\right]$$

We can then compute the test statistic ‘t’:

$$t = (\overline{x_1} - \overline{x_2})/\sqrt{\left(\frac{s_1^{\,2}}{n_1} + \frac{s_2^{\,2}}{n_2}\right)}$$

A.1.3 Determine the critical t-value and testing the “null” hypothesis.

For our study, we assume a significance level of 0.05 in a two-tailed test. Armed with ‘t’ and ‘df’, we can determine the critical t-value from a t-table (Excel function T.INV.2T(0.05, df)).

If the absolute value of our t-statistic ‘t’ is less than the critical t-value, we fail to reject the “null” hypothesis, i.e., there is no significant difference between the observed values of the two samples; in other terms, the measured differences could be due to testing noise.

If the absolute value of “t” is greater than the critical t-value, we reject the “null” hypothesis, and the two observed values are statistically different; in other terms, the process caused the measured difference to exceed the noise of the testing.

A-2 Using the concept of “Significant Difference”

The other approach is to consider the noise of the tensile testing itself. If the difference between two sets is above the noise then we can be confident that the difference is real. To that end, we define the statistically Significant Difference at a 95% Confidence Interval for each mechanical property. An observed difference above the significant difference would give us confidence that the change in value is due to the process, not the testing. Conversely, a value below the significant difference would mean that the observed difference is probably due to the testing, not the process.

The size of our study provided more than enough data to derive the necessary statistical information:

	YS [MPa]	TS [MPa]	UE%	TE%	n-value	r-value
Number of Tests	615	615	610	610	553	606

Table A-1: Number of individual test results for each property[1].

Because the testing covered multiple coils, both before and after leveling, our first step was to normalize the test results to the average value of each sample, as shown below:

	Angle to Rolling Direction	Test Date and Time	Thickness	0.2% Offset Yield Strength, $R_{p0.2}$, YS	Normalized ys_i = YS_i / Avg(sum(YS_i=1-to5))
			(mm)	(MPa)	
1	0	4/8/25 10:40	1.10	138.07	0.9986
2	0	4/8/25 10:44	1.10	138.42	1.0012
3	0	4/8/25 10:47	1.10	137.50	0.9945
4	0	4/8/25 10:51	1.10	138.17	0.9993
5	0	4/8/25 10:57	1.10	139.14	1.0064
Standard deviation	0		0.00	0.60	
Mean	0		1.10	138.26	
Range	0		0.00	1.64	

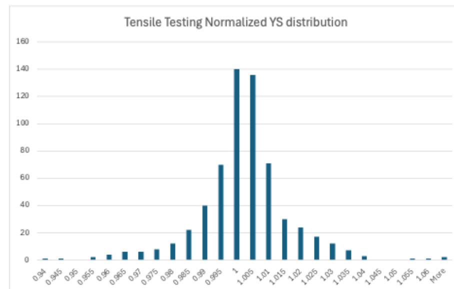

Figure A1a & A1b: Normalizing the tensile test and "normalized YS" distribution.

Repeating for all our test results, we confirm that we have a normal distribution centered around 1 (100%), and we can compute the required statistics:

	YS	TS	UE%	TE%	n-value	r-value
Average	100%	100%	100%	100%	100%	100%
Std Dev	1.38%	0.92%	3.71%	6.38%	1.75%	7.67%

Table A-2: Statistical results of the normalization of the tensile test properties.

The next step was to compute the significant difference at 95% CI. If we assume that we are comparing two groups of five samples each, the Standard Error for each group's Mean (SEM) is then:

$$SEM_i = \sigma/\sqrt{5} \text{ , where i = 1, 2.}$$

[1] We have different numbers of test results because of test failures, but we still have a population large enough to derive our test statistics.

The Standard Error of the Difference between the means is then:

$$SE_{diff} = \sqrt{(SEM_1^2 + SEM_2^2)}$$

In our case, we know that we are pulling samples from a population with the same standard deviation, so that $SEM_1 = SEM_2 = SEM$, and we can simplify:

$$SE_{diff} = SEM * \sqrt{2}$$

The use of the z-factor is acceptable since we are dealing with properties that have a normal distribution. For a two-tailed 95% Confidence Interval[2], $Z_{critical} = 1.96$ and the Significant Difference at 95% CI (SD) is:

$$SD = Z_{critical} * SE_{diff}$$

Applying to each of the tensile properties:

	dYS	dTS	dUE%	dTE%	dn-value	dr-value
Normalized Significant Difference	1.71%	1.14%	4.59%	7.91%	2.17%	9.5%

Table A-3: Normalized significant differences at 95% CI.

By substituting actual test values, we can calculate the real test significant differences for our 6xxx aluminum outer quality thin gage auto body at age six months. To be conservative, we selected the average values of all the tests involved in the study. Table 5 shows the results of such computations:

dYS [MPa]	dTS [MPa]	dUE%	dTE%	dn-value	dr-value
2.3	2.8	-1.0	-1.9	-0.005	-0.07

Table A-4: Significant differences at 95%CI in the rolling direction.

Practically, it means that we could only accept that the leveler caused a significant hardening in the rolling direction if the measured YS increase exceeded 2.3 MPa.

The same calculations can be made for the mechanical properties in the diagonal and transverse directions.

[2] in Excel, function NORM.S.INV(1-0.025)

Appendix B – Normalizing the description of the levelers

As mentioned in the introduction, levelers come in many different configurations, some with as few as three over four rollers, to some with more than 20 rollers on each bogie; some have small diameter rollers, some have much larger rollers. To compare various levelers, it would be advantageous to describe the leveler and its settings by a single numerical value.

One way to accomplish this is to add the bending and unbending events on the upper and lower surfaces of the sheet. To that effect, we define the normalizing coefficient 'W':

$$W = Sum\ of\ the\ plastic\ strains\ on\ both\ the\ upper\ and\ the\ lower\ surfaces$$

Simplifying, we assume a neutral fiber in the middle of the sheet thickness, so that:

The tension plastic strain, $T_p = \left(\frac{(R+t)}{(R+0.5*t)} - 0.2\%\right) - 1$

And its compression equivalent, $C_p = (\frac{(R)}{(R+0.5*t)} - 0.2\%) - 1$

Where: R = roller radius

T = sheet thickness

0.2% is the assumed standard elastic limit.

Each surface will alternate between tension during a concave bend across a roller, followed by compression during a convex bend against the next roller.

Let's consider the pair of rollers on the left: pushed by the upper roller, the sheet first bends around the lower roller, stretching its upper surface before compressing it by bending the other way around the upper roller.

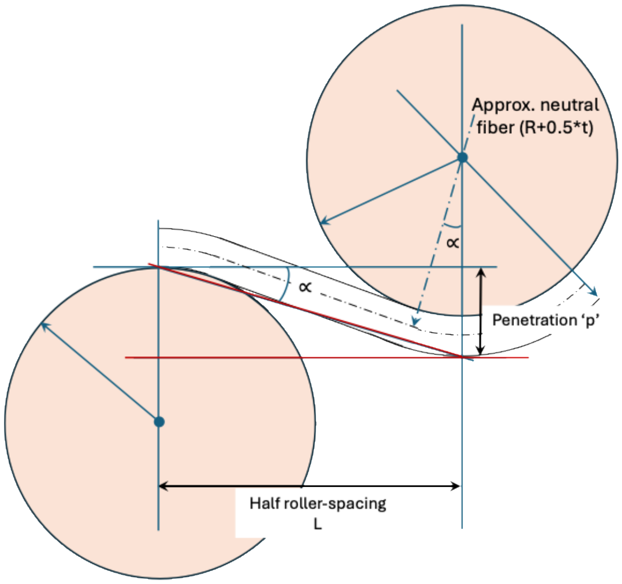

Figure B-1: Simplified schematic of a sheet segment and a lower/upper roller combination.

We can define the following parameters:

'L' = half roller-spacing

'p' = penetration of the upper roller in the space defined by two lower rollers

$$p = P + t \ ,$$

Where P is the position of the upper roller defined by the controls in such a way that P = 0 means that the upper roller shares the tangent plane defined by the lower rollers. P is positive as the upper roller goes deeper between the lower rollers.

- The contact angle $\propto$ is a function of the penetration 'p'.
- When 'p' is small relative to the roller diameter 'R', we can approximate the angle:

$$\propto \ \cong \mathrm{atan}(\frac{p}{L}) \cong \frac{p}{L}$$

Since each upper roller is higher than its predecessor, the successive rollers have diminishing penetrations. Consequently, each lower roller exit angle is less than the entry angle.

We can compute the penetration for each successive upper roller, based on the height difference between the last and the first roller H:

$$H = (exit - entry)$$

The height difference between rollers, $dp = H/(n_{upper} - 1)$

And so, the penetration for each successive upper roller is:

$$p_{i+1} = p_i + dp$$

The first and last wraps only involve only one-half of their respective lower rollers.

As long as the contact angle $\propto_i > 0$, we can then write their respective wrap angles, where 'n' is the number of upper rollers:

- For upper rollers: $w_{Upper} = 2 * \sum_1^n \propto_i$
- For lower rollers: $w_{Lower} = \ \propto_1 + \propto_n + \sum_1^{n-1}(\propto_i + \propto_{i+1})$

We can then define:

$$W = 10 * \left(w_{Lower} + \ w_{Upper}\right) * (T_p + C_p)$$

We amplify ‘W’ by a factor 10 to simplify the plotting of the results, remembering that ‘W’ is an arbitrary single term descriptor of a leveler and its settings and nothing else.

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