Aluminum Galling & Lubrication for Automotive Applications

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One cannot talk about galling without mentioning lubrication and its special place when forming aluminum auto body sheet (ABS). For clarity, this publication will simply talk about aluminum and steel sheet when referring to the respective auto body sheet.

It is necessary to go back to some basics of aluminum formability to help focus this discussion, specifically regarding aluminum sheet's behavior in draw.

Galling was one of the follow-up topics to the 2022 aluminum formability seminar. Watch the replay: Automotive Body Sheet Formability and Stamping Webinar.

Aluminum has a face-centered-cubic crystalline structure (Figure 1) that limits its drawability.

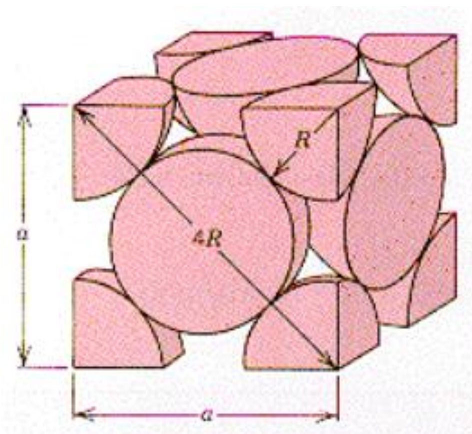

Figure 1: Face-centered-cubic (FCC) crystalline structure
(From Callister, "Materials Science and Engineering," Wiley 1997)

In mechanical testing, the anisotropy ratio (r-value or Lankford coefficient) is defined as the ratio of the width to thickness deformations expressed as true strains (more on this below). The important point is that the r-value describes the natural ability of a sheet to exchange width for length without excessive thinning. An FCC structure limits the maximum r-value to about one. Table 1 below presents some generic tensile test properties for a high formability CR4 mild steel, 5182 aluminum and a high-strength, dual-phase DP 330/590 steel.

	CR4	5182	DP 330/590
YS [MPa]	160	125	360
TS [MPa]	300	275	650
UE%	**27%**	**21%**	**17%**
TE%	**45%**	**25%**	**26%**
n_4-6%	0.243	0.335	0.19
n_10-20%	0.241	0.260	0.160
r_0	**1.70**	**0.70**	**0.90**
r_45	**1.60**	**0.75**	**1.10**
r_90	**2.10**	**0.65**	**1.15**
r_bar	**1.75**	**0.71**	**1.06**

Table 1: Generic mechanical properties of three ABS grades

To better understand r-values, assume a cube with a generic volume of one, described by δx = δy = δz = 1. Based on that, this paper assumes the volume will remain constant during deformation, or that V = δx * δy * $\delta z = 1 = cst.$

As the sheet is deformed, the unit cube will deform without changing volume. Calling e_i the relative engineering strain in each direction, the equation then becomes:

$$(1) \qquad (1+e_x) * \left(1+e_y\right) * (1+e_z) = 1 = cst$$

This publication shows a cleaner equation by switching to logarithmic space that defines the true strains $\varepsilon_i = \ln(1+e_i)$ and the equation (1) becomes:

$$ln(1+e_x) + ln\left(1+e_y\right) + ln(1+e_z) = ln(1) \iff$$

$$(2) \qquad \varepsilon_x + \varepsilon_y + \varepsilon_z = 0$$

Using the definition $r = {}^{\varepsilon_y}/_{\varepsilon_z} \iff \varepsilon_z = {}^{\varepsilon_y}/_{r}$, further substitution finds:

$$\varepsilon_x + \varepsilon_y * \left(1 + \frac{1}{r}\right) = 0$$

And finally, compute the value of ε_x given a known value of ε_y:

$$(3) \qquad \varepsilon_x = -\varepsilon_y * \left(1 + \frac{1}{r}\right)$$

Equation (3) will help show the practical implications of low r-values. Considering a simple numerical example, where a particular geometry requires a 15% compression in the y-direction.

The three cases yield:

r_bar	1.75	0.71	1.06
e_x	29.1%	47.9%	37.1%
e_y	-15.0%	-15.0%	-15.0%
e_z	-8.9%	-20.5%	-14.2%

Table 2: Influence of r-value on elongation required to absorb a 15% compression

A 29% stretch is well within the capabilities of a CR4, and even a DP 330/590 can achieve the 37% necessary to resorb a 15% compression. However, 48% is well beyond the ability of 5182 (Figure 2).

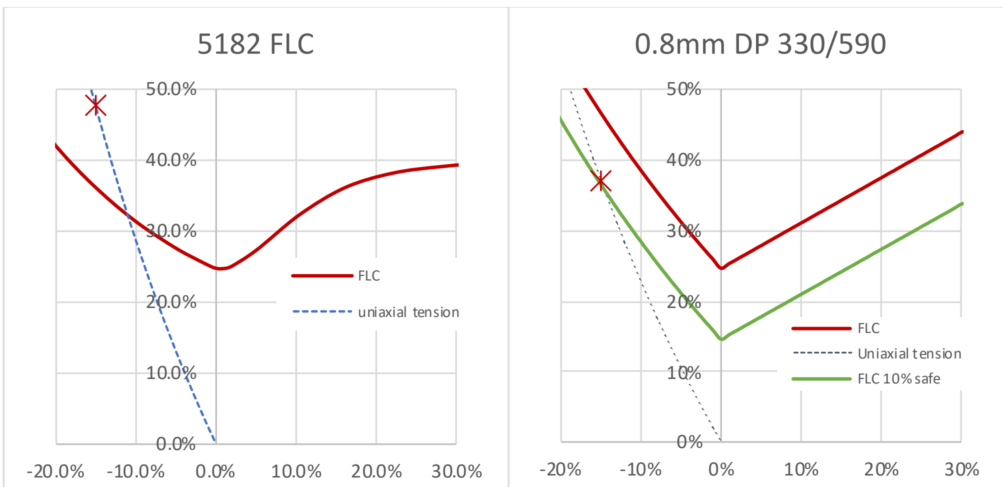

Figure 2: Strain states to absorb a 15% compression naturally

In practice, corners are formed in a draw die, where the sheet is held in a binder while being drawn. The above example assumed an unsupported sheet, where the required compression was absorbed naturally in a tensile test-like situation, without the need of a binder. In a draw die, the binder pressure prevents the onset of wrinkles thus allowing machinists to achieve higher compressions than the r-value might imply. The pulling forces that move the metal into the corner have a material specific component (forcing the exchange of width for length) and a friction component created by the binder pressure and the effort of pulling the metal over the corner radius. The lower the r-value, the higher the material specific forces, and the higher the relative binder tonnage required to prevent the onset of wrinkles. Fortunately, because aluminum work hardens better than steel, it can partially overcome its inherent lower drawability by more easily generating these higher pulling forces.

Better lubricant performance lowers the friction component of the pulling forces, helping the metal flow into the corner. This is well known to practitioners, but aluminum's inherent lower drawability makes better lubricants a necessity (Figure 3).

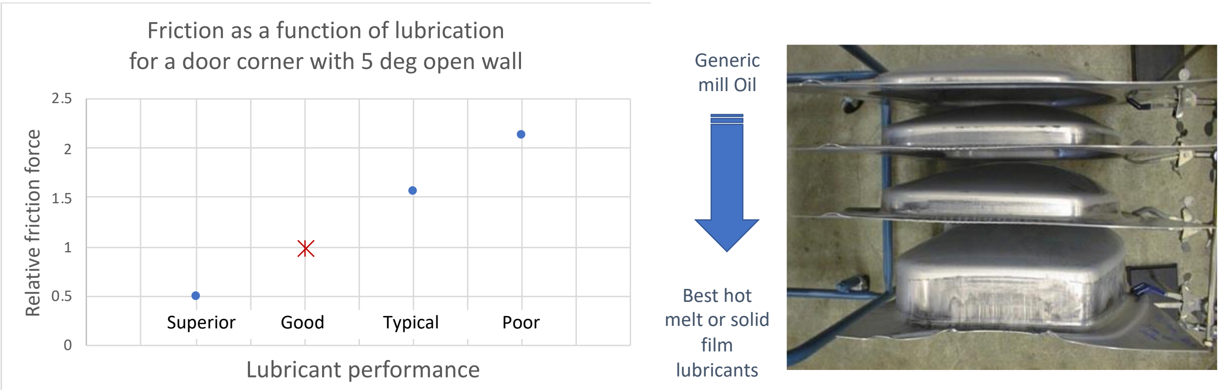

Figure 3: Lower friction coefficients are critical to deep corners in aluminum
(Picture courtesy of Novelis)

The job of a stamping lubricant is more than just separating the sheet from the tool: It must be compatible to the processes ahead of the draw die, including blanking, storage and de-stacking in front of the press. Furthermore, the lubricant protects the sheet from corrosion before and after stamping, as well as the tooling surfaces. Finally, as automakers resist having to clean parts between stamping and assembly, the lubricant must be compatible with all the downstream processes, such as welding, adhesive bonding, sealing and paint. In short, modern stamping lubricants are not standalone products, they are fully integrated into the whole manufacturing chain, and require a complex and lengthy approval process before they can enter production.

Surface texture is one of the sheet-specific parameters that can influence the performance of stamping lubricants. The traditional understanding is that the lubricant needs to cover all the peaks to fully separate the sheet from the tool. In this model, the height of the micro-asperities on the surface not only influence the amount of lubricant needed, but the asperities hold pockets of lubricants that can be brought to bear as the sheet is moving against the tool. Mill-finish sheet exhibits a strongly directional texture, while Electrostatic-Discharge-Texturing (EDT) can create a more uniform one (Figure 4).

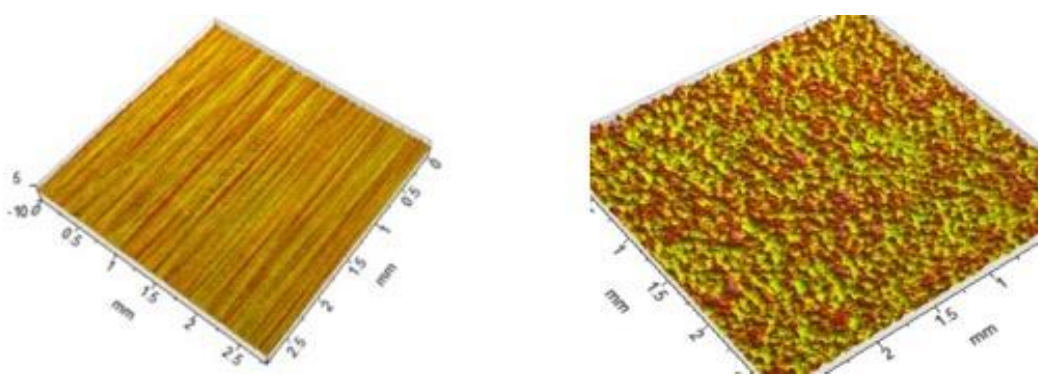

Figure 4: Mill finish surface on the left, EDT surface on the right (Courtesy of Novelis)

The effect can be pronounced with some traditional lubricants (Figure 5), while some advanced lubricants have properties capable of masking surface texture, limiting the usefulness of EDT surfaces.

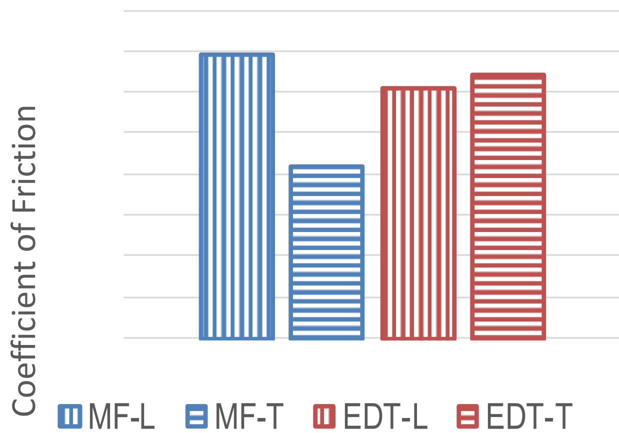

Figure 5: Typical draw bead simulator results for traditional wet lubricants (Courtesy of Novelis)

All the discussion so far has assumed the presence of lubricant in the first place, but what happens when there is no lubricant on the surface? It can happen when the lubricant fails under extreme conditions, or sometimes because the lubricant happens to not even be on the surface in the first place. Lubricants can migrate from the surface during extended storage, or under excessive stack heights, and failures in the lubrication in front of the draw die can leave dry spots.

This brings us back to the original concern—galling. Galling is an unintended friction-welding event between the work sheet and the tool. It occurs when three conditions are met:

1) Direct contact between the work sheet and the tool;
2) A contact energy high enough to rip material from one of the two surfaces; and
3) A receiving surface with enough chemical affinity for the donor material to adhere to it.

Tool steels have a much harder surface than aluminum ABS, so the sheet is always the donor material accumulating on the tool. Once initiated, galling is generally a runaway event leading to a production interruption and some manual intervention. Even in its most benign form, or when conditions become self-limiting, galling is a highly undesirable phenomenon that always requires tool rework.

It is already concluded that galling can only occur in the absence of a lubricant film, so the first line of defense in the draw die is a high-performance lubricant. Such a lubricant will perform well even under the highest combination of contact pressure and relative travel. Used in combination with a delivery system that will coat the entire work sheet it will help eliminate galling in the draw die. Semi-solid and solid films are very attractive in that respect, but they also present a unique challenge for the trim dies. Unlike a wet, self-healing, lubricant, a semi-solid or a solid film does not travel with the moving steel (Figure 6). Without proper countermeasures, galling can occur before the first hundred cycles.

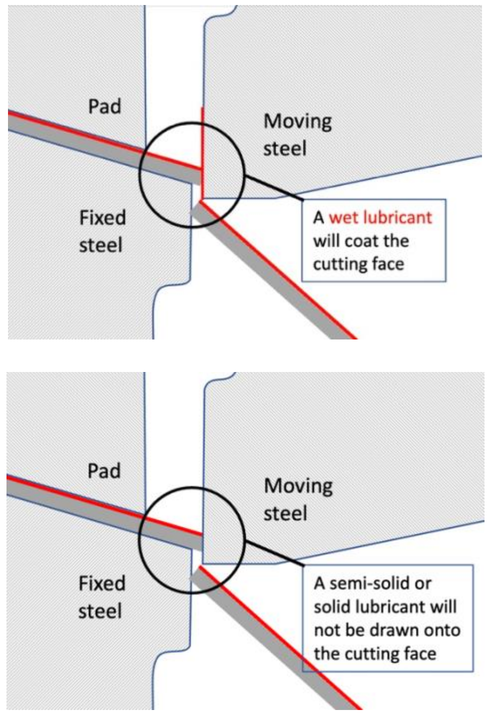

Figure 6: Unlike solid or semi-solid lubricants, wet films coat the tool cutting face

Faced with the problem, die makers have two solutions. First, lubricate the cutting face in some fashion, usually with a saturated felt strip attached to the pad. Each stroke rubs the oiled felt on the tool face, depositing the needed lubricant. The difficulty is to ensure a steady supply of lubricant to the felt, without having it drip onto the work piece. It is a solution often adopted on blank dies where the cutlines are two-dimensional. However, it is usually too complicated to implement on trim dies with their complex three-dimensional cutlines.

The second solution is to apply a specialized coating to the cutting steel. Aluminum ABS presents a unique situation, because of the presence of aluminum oxides. These oxides are often used on sandpaper because they are among the hardest known substances. Any coating of lower hardness will literally be sanded off over time, so the desired surface should be harder than the hardest of the aluminum oxides, meaning diamond level hardness. Another requirement of the coating is that its application method should not jeopardize the tool steel characteristics. Furthermore, it should be hard and tough to survive the high point-loads at the cutting edge. Finally, it should provide some level of inherent lubricity to minimize the contact energy. In practice, diamond-like carbon (DLC) coatings have proven themselves as the only solution, simultaneously providing high surface hardness, toughness, and graphite-like lubricity.

Summary

Proper lubrication is essential to fully take advantage of aluminum ABS formability characteristics. However, the extreme pressure (EP) additives that react with steel to form lubricious metallic salts will not react with aluminum to provide the same benefits. Dedicated solutions are therefore indicated. Stamping lubricants must exist in the context of the entire manufacturing process, from blanking through assembly and paint. Hence, they are a cross-functional product, and it is best to discuss specific solutions with the entire manufacturing team and a reliable lubricant supplier.

Galling in the draw die is a lubricant failure and should never occur if using stamping lubricants good enough to fully take advantage of the forming capabilities of aluminum sheet.

Galling on the upper trim steel faces can be solved by a DLC coating applied over a suitably prepared tool steel.

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