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A BETTER WHEEL

Calculating active and passive stresses exerted on wheels during competition, or: why your wheel just broke

WORDS Jeff Zurschmeide
TECHNICAL EXPERTISE David Schardt, president of Forgeline Wheels

One thing is true of every car that competes in SCCA: they all ride on wheels. Whether it's an original Morris Mini rolling on 10-inch stamped steel wheels or a Porsche 911 GT3 RS with center-lock carbon fiber 21s, we all use wheels, and we all tend to take them for granted. But just as much engineering goes into a good set of racing wheels as into any other part of the car, and thanks David Schardt at Forgeline Wheels, we received an indepth look at the process.

Racing wheels must meet certain basic requirements, and only a few of these are well understood by the average racer. First, a racing wheel must have the correct rim width, offset, center bore, lug bolt pattern, and brake clearance. That much we all know. But racing wheels should probably be light in weight and offer high stiffness, resistance to corrosion, impact resistance, and be easy to clean and repair. According to some, a racing wheel should also be designed to perform for at least three race seasons (roughly 10,000 race miles) without a structural failure. On top of all that, we'd like them to be good looking on the car, too. That's a lot to ask - but mostly we just expect it to happen.

But before selecting a wheel for racing, there are two important areas that should not be overlooked: Items that affect the life of the wheel's ability to withstand the racing loads.

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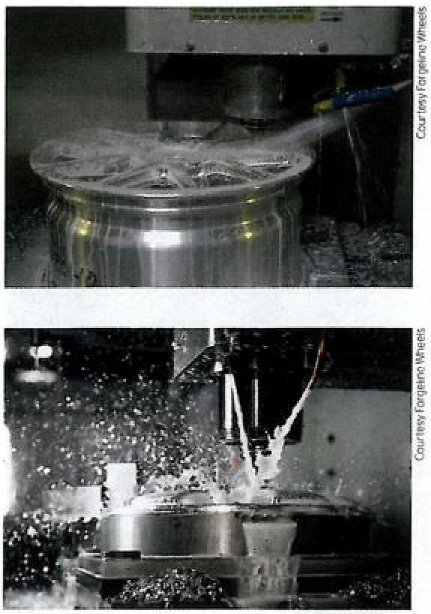

Courtesy Forgeline Wheels

Courtesy Forgeline Wheels

BUILD IT RIGHT

(ABOVE) A wheel's design and construction method can differ based on materials and the environment in which the wheel will be used. Companies like Forgeline use exacting production methods to ensure each wheel will hold up to the needs of the user.

Many factors can affect a racing wheel's functional life. The average racing wheel goes through far more sets of tires than its street-going cousins, and it operates under much harsher conditions. Wheel life factors include the base material the wheel is made from, the type of tires used, the weight of the car, downforce exerted on the wheels, and any damage the wheel may suffer. You also have to allow for the occasional manufacturing or materials defect.

Materials currently used in racing wheels include cast aluminum, forged aluminum, magnesium, and carbon fiber. Of course, steel is still in use, too, but except in classes like Formula Vee, steel has largely been replaced with alloys in SCCA racing.

Wheel materials are selected for several important factors including strength (must be strong enough to withstand required forces), elongation (high elongation allows bending instead of breaking), fatigue resistance (must withstand many cycles at high stress), specific gravity (lower density provides lower weight per volume), raw material cost (adds to final price), and ease of manufacturing (difficult manufacturing adds to price).

The Wheel Materials Comparison chart in this story details the tradeoffs inherent in differing wheel materials. Predictably, wheels with high ratings in some areas have less attractive ratings in others - usually in the form of a high price for materials like carbon fiber, forged aluminum, or magnesium. Tensile and yield strength, respectively, represent the stresses in pounds per square inch (psi) that would cause breakage or start to deform the material. Elongation demonstrates the percentage of stretch the material would endure before breaking. Any of these materials would make a satisfactory wheel. However, certain materials would allow a stronger, lighter wheel, but at a higher price point. *(See Figure 1a and 1b)*

Wheel life is directly related to the stress occurring from side forces generated by tire friction. Tires can be considered to fall into three different classifications: street tires, DOT race tires, and racing slicks.

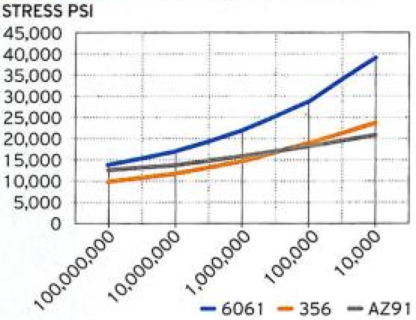
Street tires can have a friction coefficient from 0.7g to 1.0g depending on the treadwear rating. In the 1970s, the tire friction coefficient was generally in the range of 0.7g to 0.8g. However, today's high-performance tires can have a much higher coefficient of friction. Tire Rack performed a study between 2002 and '10 to show the current relationship between tread wear and tire friction coefficient. The results found by Tire Rack clearly demonstrate the load curve when the tread-wear rating improves.

DOT race tires are another step up from high-performance tires and have a coefficient of friction in the 1.2g range. Race slicks can have a friction coefficient of 1.5g or more depending on construction, compound, car weight, and car speed. Also note, that even though the coefficient may be specified as only 1.5g by the manufacturer, cars with downforce will have an apparent coefficient well above 1.5g. *(See Figure 2)*

Outside of side forces, there are two other major loads to consider: static load measured with the car at rest, and downforce load from wings or body shape. The static load on a wheel is normally half the axle weight at the heaviest end of the car. On the other hand, downforce load must be measured with onboard sensors or using manufacturer's data because downforce is created only when the car is moving.

Static and downforce loads will have the greatest influence on wheel life because both loads combine with the tire friction to produce the total side force. As will be discussed later, it will be shown that adding 10 percent additional load on the wheel will cut the wheel life by 50 percent.

WHEEL MATERIALS LIFE CYCLES VS. STRESS *(Figure 1b)*



TIRE FRICTION COEFFICIENT AND TREADWEAR *(Figure 2)*

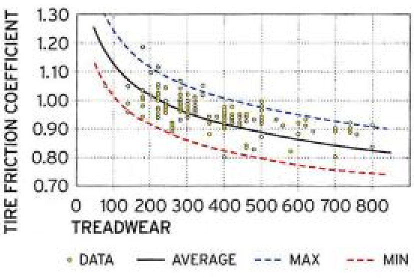


Figure 2 data courtesy Tire Rack

WHEEL MATERIALS COMPARISON *(Figure 1a)*

	Tensile strength	Yield strength	Elongation	Endurance limit*	Specific Gravity	Cost	Ease of Production (1=easy;10=hard)	Wheel price range
6061 forged aluminum	45,000psi	40,000psi	15%	14,000psi	0.100 lbs/cu-in	$1.80/lb	6	$800-,1500
A356 cast aluminum/Flowform	29,000psi	24,000psi	4%	10,000psi	0.100 lbs/cu-in	$1.00/lb	3	$100-$500
AZ91T6 cast mag	40,000psi	22,000psi	6%	13,000psi	0.066lbs/cu-in	$1.70/lb	4	$1,000+
Carbon fiber	200,000psi	200,000psi	2%	150,000psi	0.060lbs/cu-in	$15.00/lb	10	$2,000-$3,000
Steel 1015	60,000psi	40,000psi	35%	30,000psi	0.280lbs/cu-in	$0.30/lb	3	$25-$75

** Endurance limit: material will not fail up to 100,000,000 cycles at this stress*

Philip Royle

GOOD WHEELS GONE BAD

From spectacular seperations (ABOVE) to mangled edges (LEFT), many factors figure in to a wheel failure. Some are preventable while others are simply unavoidable.

A primary consideration when purchasing a wheel should be the load rating that is placed on the wheel by the manufacturer. All reputable manufacturers mark each wheel with a load rating. The load rating certifies the wheel will perform adequately without failure with street tires on normal road use.

The standard procedure for determining the load rating of a wheel is to use the Society of Automotive Engineers (SAE) formula from specification J2530. Alternate procedures used are the Japanese JWL and German TUV, but all of these use the same formula.

First, the following formula is used to calculate the side forces that will be seen on the wheel: $S = L\,[(R*u)+d]/12$. In this formula, "S" is the number of foot-pounds of side force on the axle, "L" is the total load on the wheel including static and downforce in pounds, "R" is the radius of the tire in inches, "u" is the coefficient of friction of the tire or g-force seen by the vehicle, and "d" is the offset of the wheel in inches.

By applying this formula, finite element analysis can be used on the wheel design to determine if the stress would exceed the limit. With the wheel held fixed, a force of "S" is applied to the axle to determine the stresses that occur throughout the wheel. If a wheel is to be expected to have a life of 10 million cycles, then the stress at any point in the wheel cannot exceed the stress shown earlier in this story for 10 million cycles. In the case of forged 6061, this would be 17,000psi. But to verify the result, the wheel must undergo an actual fatigue test to confirm that the wheel will not fail.

This analysis is performed with the Rotary or Cornering fatigue test and it is very important since the highest stresses occur during cornering. In this test, the wheel is rotated at high speed while the force "S" is applied to the axle. But since it is not feasible to run a test for 10 million cycles, an accelerated test is used. Two additional tests are commonly run to verify other structural capabilities. In the radial fatigue test, a wheel (with a tire mounted) is subjected to twice the normal straight rolling load for over a million cycles. This test will generally create cracks in the tire bead seat area if inadequately designed. The impact test, (with tire mounted), is performed by dropping a weight on the edge of the rim. The wheel should not deform or crack to the point of air loss. In the case of a wheel rated for 1,300lbs, a weight of 535lbs would be dropped from nine inches.

So far, our discussion on determining wheel load ratings has used the formula for wheels as used on the street, with tires that produce a low coefficient of friction and have no downforce - not exactly what is found in the SCCA. So, it should be noted that in the case of an aluminum wheel, increasing the load by 10-12 percent will decrease wheel life by 50 percent.

There's a fancy calculation you can use for this, but the end result can be seen in the Wheel Load Rating Adjustments chart. *(See Figure 3)*

Note that at the higher friction, the stress on the wheel increases dramatically and the load carrying capacity is diminished. Using racing slicks would drop the load rating on a wheel by 50 percent. If the wheel was used on a 3,000lb car with 50/50 weight distribution and DOT competition tires, the 1,300lb rating would be sufficient. However, the same wheel with racing slicks would not be acceptable because the load rating would be reduced to 663lbs. Additionally, should the same wheel be used on a car generating 100lbs of downforce per wheel, another 100lbs would need to be deducted from the load rating.

WHEEL LOAD RATING ADJUSTMENTS *(Figure 3)*

APPLICATION *(load-rated 1,300lb)*	g-force	Stress	Adjusted load *(without downforce)*	Adjusted load *(100lbs downforce)*
SAE Street racing at wear rating 550+	0.7	1,354psi	1,300	1,200
Autocross at tread wear rating 100-200	1	1,842psi	956	856
DOT competition tires	1.2	2,167psi	812	712
Racing slicks	1.5	2,654psi	663	563
Prototypes and high downforce	2.5	4,279psi	411	n/a

When downforce is added to the equation, the apparent coefficient of friction and side force on the wheel increases dramatically. For vehicles generating very high downforce, the tire friction is still in the range of 1.5g. However, onboard data acquisition will record much higher readings.

The reason for this can be seen by running the SAE formula with the downforce added to the static weight on the wheel. Under these conditions, the stress (S) is: S=(W+D)*u. For an example using a 3,000lb car, 50/50 weight distribution, 2,000lbs of downforce, and "u" of 1.5g, the calculation is: S=(750+500)*1.5=1,875ft-lbs.

To obtain the apparent coefficient of friction, the stress is equal to the static weight times the friction, so: 1,875=750*U, where "U" is the apparent coefficient of friction, or g-force.

The equation works out like this: U=1,875/750=2.5. In actual conditions, if data acquisition is used to find lateral g-forces, that force should be used along with the static weight to calculate the side force stress on the wheel.

This article has probably delivered more mathematics than you ever expected to think about when it comes to your racing wheels. In most cases, it won't be necessary to do any calculations, but drivers of heavier vehicles with substantial downforce and racing tires should absolutely run these calculations to see how their wheels are likely to hold up. The average SCCA Club racer on DOT tires can also benefit from knowing when a given set of wheels should be replaced.

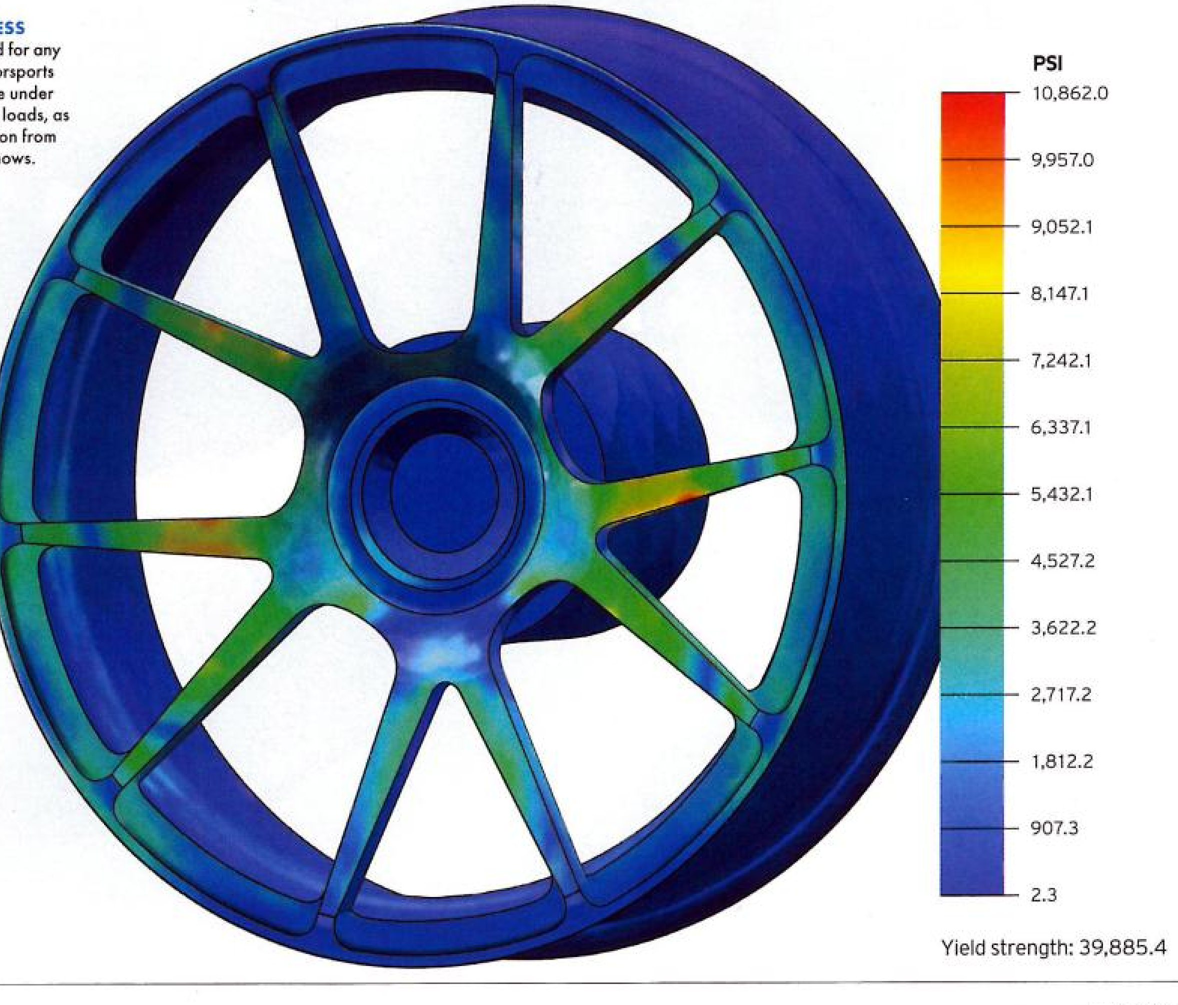
When researching a new set of wheels, at a minimum, you should take a few things into consideration, like the weight of your vehicle, the type of use (street, autocross, road race), the type of tires being used (ensuring the load rating listed on the wheel is truly accurate for your needs), and whether your vehicle has additional downforce. To assist customers in selecting the proper wheel and tire combination, Forgeline labels each of their wheels with multiple load ratings that depend on the type of tire used.

If you already have invested in wheels, you need to keep track of how old your wheels are, and have them inspected every tire change for signs of wear and fatigue. The cost of a replacement wheel, or even a whole set of wheels, is far less than the potential cost of a wheel breaking on the track. ◉

WHEEL DEFECTS AND DAMAGE

Any defect in the wheel material can create a point of crack propagation. Porosity in the material as small as 0.010 inch can create an early fatigue crack if it is located in a high-stress area. A dent of .040 inch in a critical area can cut the fatigue life in half. A well-manufactured wheel attempts to reduce these effects by using low porosity materials, removing sharp edges, and by applying an additional safety factor in design.

Obviously, problems can occur if the wheel is subjected to many high force curb or speed bump impacts. Even though the wheel many not sustain visible damage, the higher than normal stress from a few hundred impacts will reduce the wheel life.



HIGH STRESS
Wheels used for any type of motorsports activities are under tremendous loads, as this illustration from Forgeline shows.