How Cartridge Cases Work and Fail

By Jeff Siewert

This article will cover the principles behind proper function of cartridge cases and some of the way's cartridge cases can fail.

How Cartridge Cases Work:

Cartridge case design, done analytically, requires some fairly sophisticated computational models, as well as a skilled operator to construct the model, feed in appropriate boundary conditions and material properties inputs, as well as interpret results. Firing tests will also be required, of course, as any analytical model must be validated to provide reliable results.

The other approach to case design is empirical, which requires fabricating and fire testing a boatload of cases under a wide variety of conditions (high and low peak pressures, material processing and case material hardness, case exterior conditions like dust or lubricant, gun lock stiffness, initial case-chamber gaps, etc.) to ensure the case has enough structural robustness to transition to production.

The cartridge case is a handy, waterproof vessel that positions the primer, protects and contains the propellant, and positions the projectile in the forcing cone of the firearm. The case is also a replaceable high-pressure seal that is needed to keep the shooter safe and the gun functioning properly.

During the firing process, the case body is under stress from multiple directions from the internal pressure developed behind the projectile arising from the rapidly burning propellant. Figure 1 shows the component strains seen by each incremental section along the cartridge case. The axial strain is along the longitudinal axis of the case, the hoop strain is around the circumference of the case, and the radial strain acts to displace the case material outward in a direction perpendicular to both the axial strain and the hoop strain. Depending on the details of the interaction between the case and the chamber, the total strain at each point along the case length can change dramatically due to rapid shifts in one of the component strains.

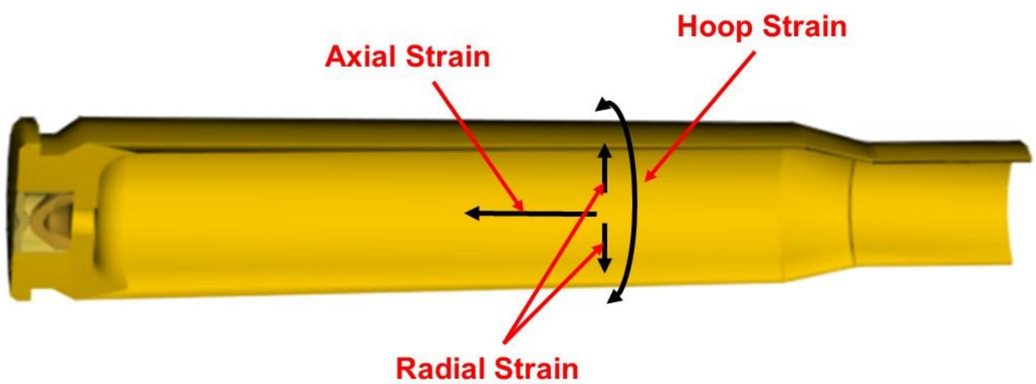

Figure 1: **Cartridge Case Strain Components**

Cartridge cases provide a reliable high-pressure seal for the chamber because of the case wall thickness taper, material properties taper and (depending on the application) the exterior taper along the length of the case body (for rifle applications). The wall thickness taper makes the case thicker near the base and thinner near the case mouth, allowing the case to seal first nearest the case mouth. The case structure works best when the case material strongest (but least ductile) is at the case base, and weakest (but most ductile) near the case mouth. This material properties gradient arrangement, combined with the wall thickness taper promotes sealing nearest the case mouth first. The case taper (for non-revolver applications) aids in case extraction after firing for cases operating at high pressures.

Since the case material in nearly all cartridge cases are subjected to stresses above the elastic limit during firing, the case body taper helps to reduce the effort required to extract the case from the chamber. The extractor lip or flange provides a convenient handle by which to grab the case and pull it from the chamber. Most importantly, the cartridge case is a robust, replaceable seal against high pressure gasses leaking aft.

Case materials with sufficiently high yield strength to avoid stress above yield (like 200 or 250 maraging steel) are hard as well as ductile, making them usually expensive to fabricate and form. Thus, these high strength materials are seldom used for case materials.

Most firearms and other structures in common usage are designed to operate well below the yield point of the material from which they are made. The “factor of safety” is a common measure of structural robustness for structures operating within their elastic limit; this is the ratio of yield stress to peak operating stress. This sort of assessment is appropriate for structures intended for multiple uses, where fatigue (failure due to repeated load application and removal) may be a factor in determining useful life. Fatigue failures start as small cracks that develop in a component at stress levels under yield stress. These cracks then propagate through the material due to repeated load cycling and resulting work hardening of the material.

Since cartridge cases are primarily designed to be “single use” items (or reused only a few times) and they are stressed above their yield point at some point along their length, the traditional “factor of safety” structural margin assessments made for typical structures really aren’t appropriate. For cartridge cases a different structural evaluation criterion is used, known as “percent of ultimate strain” to evaluate structural margins. If a material will elongate 50% before failure and a strain of 40% is caused by firing it, that item is operating at 80% of failure (40/50 = 0.80). By using a percent of ultimate strain failure criterion, an appropriate measure of the structural margin of the cartridge case is made.

There are 6 phases to the case-chamber interaction. These phases are listed in Table 1:

Phase	Description
1	Initial Conditions/Weapon Interface
2	Propellant Ignition
3	Pressure Load Increase
4	Elastic Recovery
5	Residual Clearance / Unlock
6	Extraction

Table 1: Case-Chamber Interaction Phases

Each of the phases of case operation will be described briefly below.

- Phase 1: Initial Conditions. This phase covers the interior dimensions of the chamber, exterior dimensions of the case, the lock stiffness of the weapon, initial position of the case within the chamber (headspace control), and the initial temperature of the case and chamber.

- Phase 2: Propellant Ignition. This phase covers the firing pin strike of the primer, pressure rise in the chamber and propellant ignition, case wall radial expansion to contact the chamber, projectile overcoming case retention pressure, case axial movement relative to the chamber until the base contacts the bolt face after the bullet separates from the case.

- Phase 3: Pressure Load Increase. This phase covers the deflection of the chamber post case contact, propellant combustion to peak pressure, thermal input to the case wall, through the case wall into the chamber, mechanical and thermal expansion of the case within the chamber

- Phase 4: Elastic Recovery. This phase includes decrease of pressure after the projectile exits the barrel, elastic recovery of the chamber and the elastic portion of the case deflection, continued case temperature rise in the case until internal pressure is close to atmospheric pressure.

- Phase 5: Residual Clearance / Unlock. This phase includes residual stress between the case and the chamber, as well as between the case base and bolt face, if applicable.

- Phase 6: Extraction: This phase is the application of load to the case extractor lip and removal from any residual interference between the case and the chamber.

The interaction between the case and the chamber is highly dynamic event, with multiple interacting facets to the non-linear interaction between case and chamber. The effect of these interactions can only be studied in detail with specialized equipment and analyzed with specialized software. Typically, the case first contacts the chamber near the case mouth due to the thinner case walls and lower strength case material near the case mouth. As pressures continue to rise in the case, the contact interface between the case and chamber moves aft along the case, toward the base of the case.

The following non-linearities are present when analyzing case-chamber interaction:

- A mechanical non-linearity dealing with the contact of the case and chamber
- The stress-strain behavior of the case material is typically non-linear since it has been pushed above its yield point
- The effect of the dynamic thermal event from propellant combustion on case material properties further complicates the behavior of the case material
- Since the case is (typically) tapered and it contacts the chamber at different times along the length of the case

All these factors serve to make analyses of the interaction of the case with the chamber exceptionally complex for such a “simple” mechanical device. Figure 2 shows the stress-strain behavior of a high strength brass case section and a low strength brass case section. The vertical blue line shows the case strain when the case contacts the chamber, while the vertical red line is the peak case strain. For the high strength case material, the stress at chamber wall contact is just below 70,000 PSI, while for the low strength material, the stress is about 40,000 PSI.

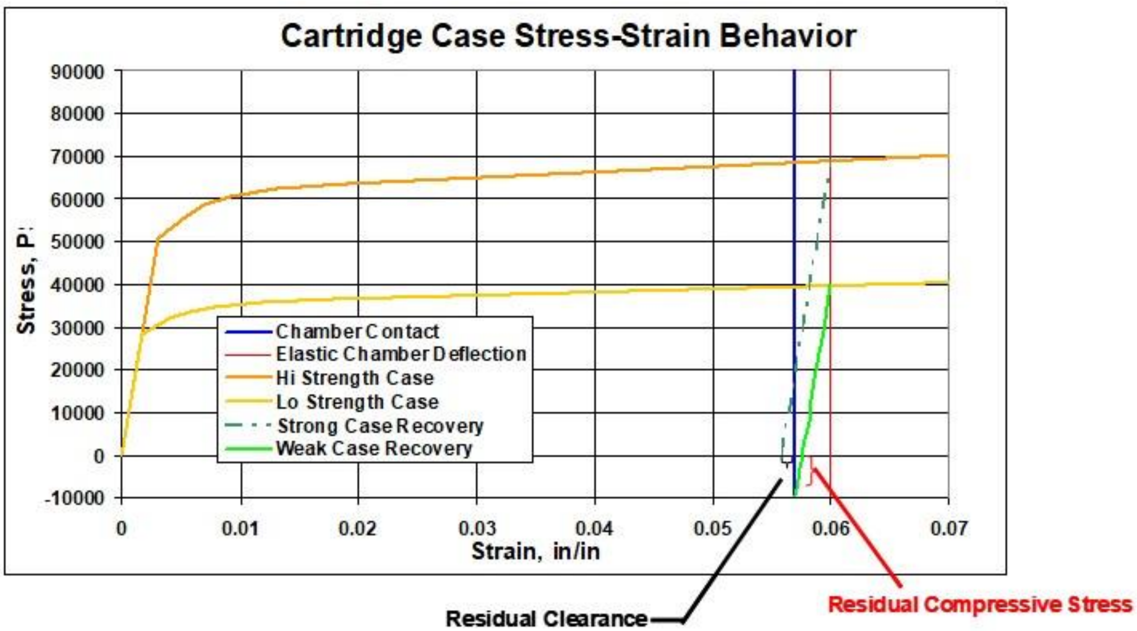

Figure 2: Cartridge Case Stress-Strain Behavior

The residual clearance and compressive stress labels in the lower right-hand side of Figure 2 highlight the case strain state as the bolt is unlocked. Residual clearance is shown for the high strength material and the residual compressive stress for a case made with low strength material is also evident. The reason for the residual clearance or residual compressive stress is the difference in stress at peak strain and the slope of the case elastic modulus, along which the case material recovers as the pressure decreases. For the high strength material, there is residual clearance as the pressure and stress decreases to zero, but for the low strength material, the separation between the case stress and zero stress isn’t large enough to prevent residual compressive stress between the case and the chamber remaining as the chamber pressure returns to zero. Thus, the lower strength case has residual compressive stress between the case and the chamber at zero pressure, requiring a tug on the case to remove it from the chamber. If there is a taper on the interfering portion of the case, it only has to be moved aft a bit to eliminate the residual interference. Straight wall cases may have to move aft a considerable distance to remove the remaining stress between the case and the chamber and allow easy removal of the case.

Cartridge cases have both a thickness gradient and material properties gradient (e.g. hardness) that help them perform the function of high-pressure seal properly. Figure 3 shows the case wall thickness as a function of distance from the case base for a small caliber case, along with the nominal case-chamber gap. Note that the gap is zero at the shoulder for this shoulder headspaced cartridge case.

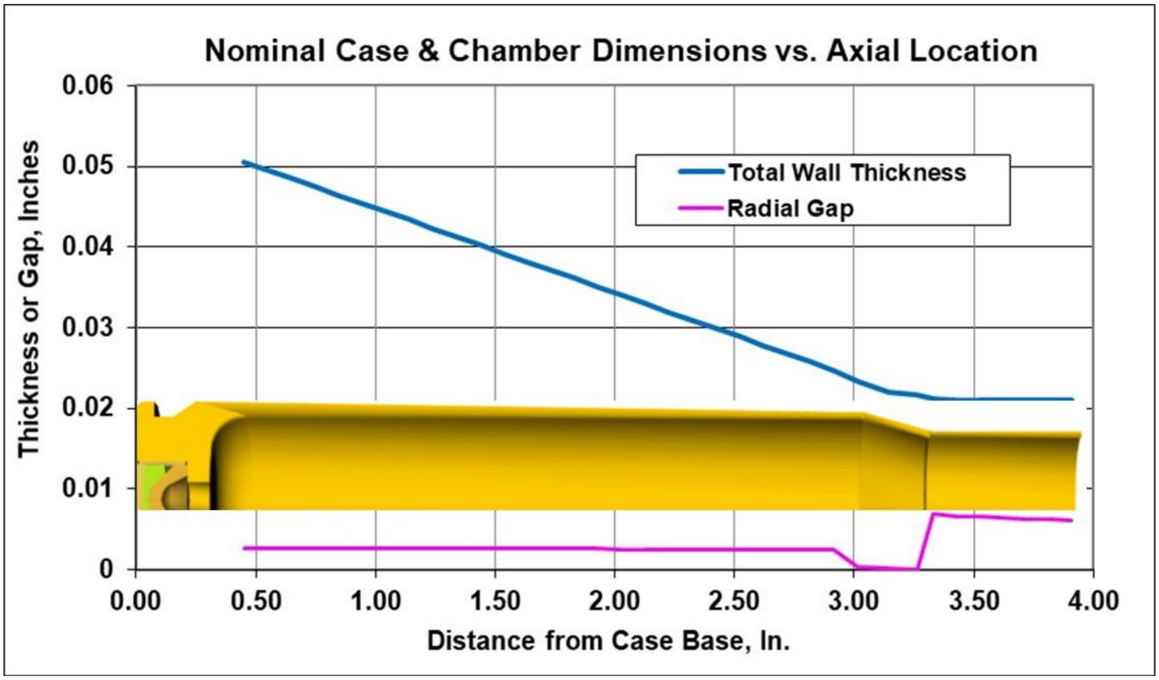

Figure 3: Case Wall Thickness vs. Distance From The Case Base

Figure 4 shows the hardness profile in a cartridge case as a function of distance from the case base. It also shows the corresponding true stress-strain behavior moving from the base (hardest, highest yield strength, lowest elongation at failure) to the case mouth (softest, lowest yield strength, and highest elongation at failure).

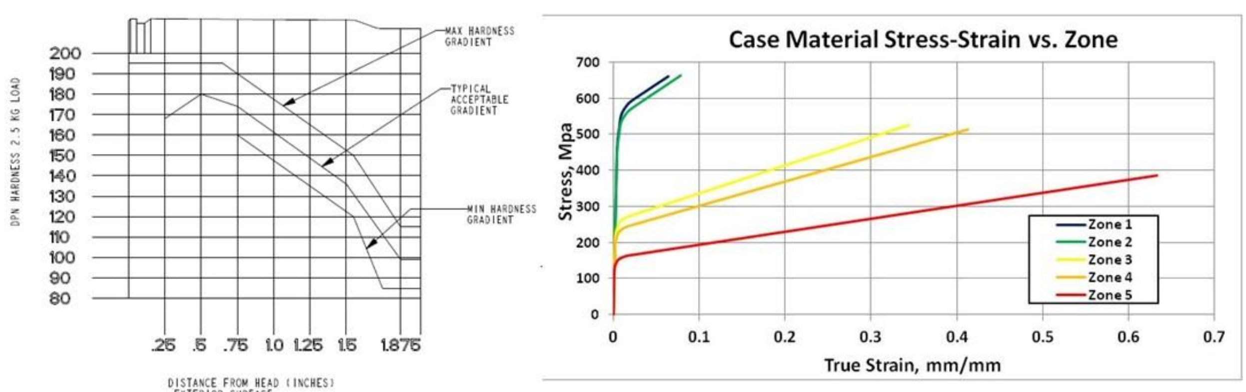

Figure 4: Case Wall Hardness vs. Distance From The Case Base & Stress-Strain Behavior

Depending on the relative mass/energy of the firing pin and the clearances between the cartridge case and the chamber, and whether the bolt face contains a spring-loaded eject pin, the firing pin may move the case forward in the chamber until the shoulder of the case contacts the shoulder of the chamber. If the cartridge mass is sufficiently low and the case is free to move, the firing pin strike can translate the case forward in the chamber until it meets the headspace stop. This forward movement of the case, or the spring loaded eject plunger, causes a gap between the case base and bolt face. For tapered cases, this forward movement provides minimum radial gap between the case and the chamber. At some point, the case meets resistance with the chamber and the firing pin energy is dumped into deforming the primer cup. The primer mix is pinched between the interior surface of the primer cup (deformed by the impact of the firing pin) and the anvil, and the primer mix detonates. The mix is converted to hot particles and gas almost instantaneously, and the pressure starts to rise in the primer pocket. If the primer cup is rigidly attached to the case primer pocket via lacquer and crimp, the primer cup cannot move aft relative to the cartridge case as the pressure starts to increase in the primer pocket. If the cup isn't held in place by the belt and suspenders of lacquer and primer pocket swage, the primer cup moves aft relative to the case as the pressure rises in the primer pocket until the cup hits the bolt face.

As the ignition process proceeds, hot, particle filled gas passes thru the flash hole(s) in the case base, transferring the flame front to the propellant bed. At this point the propellant starts to burn due to the contact of the hot particles from the primer gasses coalescing on the exterior surface of the propellant. As the propellant burns, it changes from a solid into a gas, causing the pressure to rise in the case. The case then starts to swell in both length and diameter. Ultimately, the pressure increases to the point where it overcomes the crimp and/or friction of the case mouth restraining the bullet, and the bullet is dislodged from the case. Once the projectile overcomes the case retention force and the bullet starts to move, the case can then move aft axially due to the unbalanced pressure load acting on the case. If the primer has not been properly restrained relative to the case, the aft movement of the case can pinch the primer cup between the case base and the bolt face, pinching the cup and causing structural failure.

Initially, the pressure in the case continues to rise as the projectile proceeds down the barrel from the gases evolved from propellant burning. Upon attaining a sufficiently high pressure in the case, the case wall deflects outward enough to contact the chamber and case base contacts the bolt face. Once the case wall contacts the chamber and bolt face, the case walls are supported by the strong (typically) steel structure of the firearm, and the case starts transferring thrust aft to the firearm.

The case is thinnest near the case mouth, and gets progressively thicker near the base of the case. This thickness gradient, combined with a strength gradient that puts the material with the lowest strength at the case mouth, makes the case contact the chamber near the case mouth first, causing the case to seal there early in the combustion process. As the case contacts the chamber wall, the chamber supports the case due to the mechanical stiffness of the barrel or cylinder. At the same time, if the friction between the case wall and the chamber interior is sufficiently low, the case moves aft in the chamber relative to its initial position due to the unbalanced load generated by the release of the bullet from the case mouth, eventually causing the case base to contact the bolt face.

The pressure in the case continues to rise, and the contact point between the case wall exterior and the chamber moves from the case mouth aft toward the case base, helping to prevent leakage past the case. The case stretches in the radial and hoop direction until it hits the chamber, and along the axis of the case. The stretch along the axis of the case is limited by the coefficient of friction between the case and the chamber forward of the last contact point and the internal case pressure. As the contact point moves aft with increasing pressure, progressively more contact area is engaged between the case and the chamber and more load can be reacted in shear through the contact area between the two structures. The increasing internal pressure and case-chamber contact area increases the axial load carried by the case wall, with maximum axial stretch (and hoop stretch) occurring just aft of where the case wall last touches the chamber. The large combined stretching just aft of the point of last case contact with the chamber wall causes the case wall thinning frequently seen in the aft portion of cases fired multiple times.

How Cartridge Cases Fail:

Cartridge cases that make it past the design and evaluation phases aren't expected to fail due to "structural overload" (e.g. see a region with percent ultimate strain > 100%) on the first firing, but cases can still fail in numerous ways, some of which the shooters themselves are responsible for causing.

Necking of the case just aft of the point of last contact with the chamber causes a signature, circumferential failure of the case, as shown below, courtesy of:

http://i338.photobucket.com/albums/n420/joe1944usa/338.jpg.

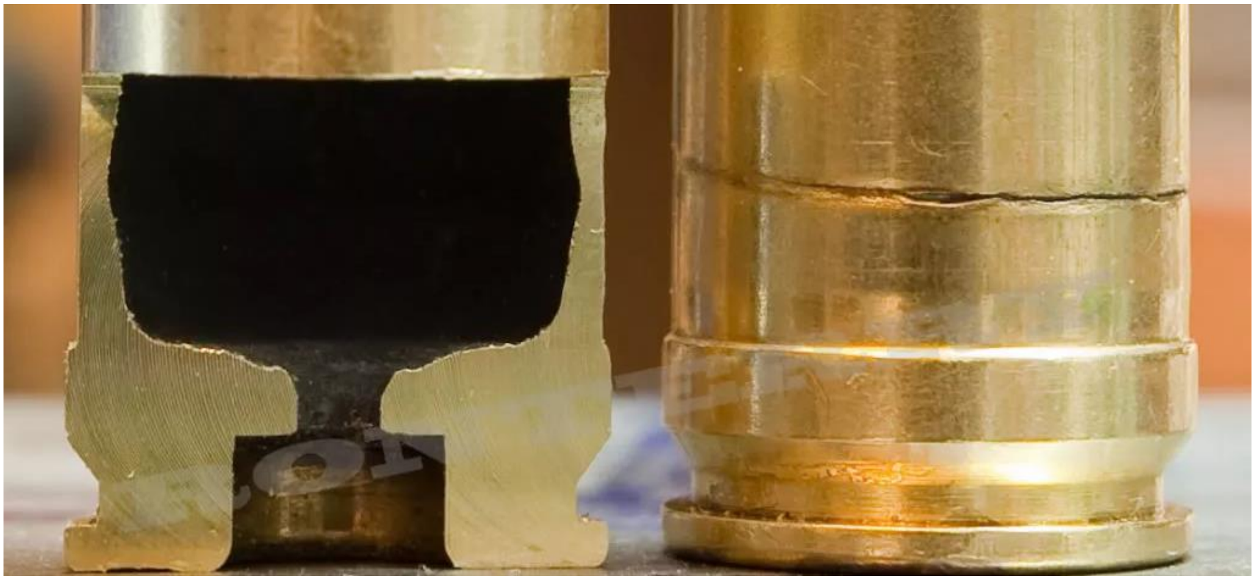

Figure 5: Case Necking Failure

This structural failure is due to:

1. Large combined strain in the section just aft of the last point of contact with the case, largely driven by the axial strain at this section
2. The low strain at failure in this section of the case caused by the high hardness of the brass.
3. Repeated sizing and firing

Another common failure caused by repeated firing and resizing of the case is shown in Figure 6. The repeated firing, and resizing causes the case to experience "cold work" which raises its yield strength, but this increase in hardness also reduces the material elongation at failure. A reduction in elongation at failure really translates into an increase in "brittleness", meaning portions of the case that once could be stretched to say 5% before the case failed can now only be stretched 3% before the material fails. Figure 6 shows a brass case that failed due to repeated firing/sizing cycling and resulting reduction of elongation at failure near the base of the case. On the left is a section through the case wall near the case base, with a red arrow indicating the failed case section. On the right is a photo of the exterior of the cases; leftmost is the case shown in the left photo, plus two other cases. The middle one has also failed, and the one on the right-hand side is about to fail. In this particular location, the case is fairly hard, but this region has little elongation as a result. These cases had been fired a maximum of four times, and there is little doubt that work hardening from repeated firing and resizing has reduced the elongation at failure in this region of the case.

Figure 6: Brass Case Leak Due to Repeated Sizing and Reduced Elongation at Failure

In a related vein, case material can be improperly processed or heat treated, leading to a case occasionally "sneaking through" the manufacturing process that will fail when subjected to "normal" firing pressures on the first shot. Figure 7 shows some examples of failures of improperly heat-treated aluminum cartridge cases. This is not to disparage aluminum cases, it serves to illustrate what can happen if the material is not processed properly.

Figure 7: Failures of Improperly Processed Aluminum Cases

A more insidious case failure can occasionally be seen in brass cases caused by a condition known as "stress corrosion cracking". Stress corrosion cracking (SCC) happens when a material that is susceptible to a particular corrosive environment also has residual internal stress remaining from the forming process. Brass is particularly corrosion sensitive to compounds containing free nitrogen (not molecular nitrogen in the atmosphere), and for most metallic cases, there is some level of residual stress left from making the case to a particular hardness. Since modern smokeless propellant contains copious amounts of nitrogen in the form of nitrocellulose, the corrosive environment is present with the case. As previously mentioned, residual stress is present from the case forming process, or it can be caused by the interference fit of the projectile into the case mouth. So, the three factors required for stress corrosion cracking are present in most brass cases.

Figure 8 shows 17 HMR cases on the left suffered from varying degrees of stress corrosion cracking during firing, while on the right, a 20x103mm brass case with stress corrosion cracking is shown. On the right, interior and exterior photos are shown, along with a microphotograph of a section through the crack.

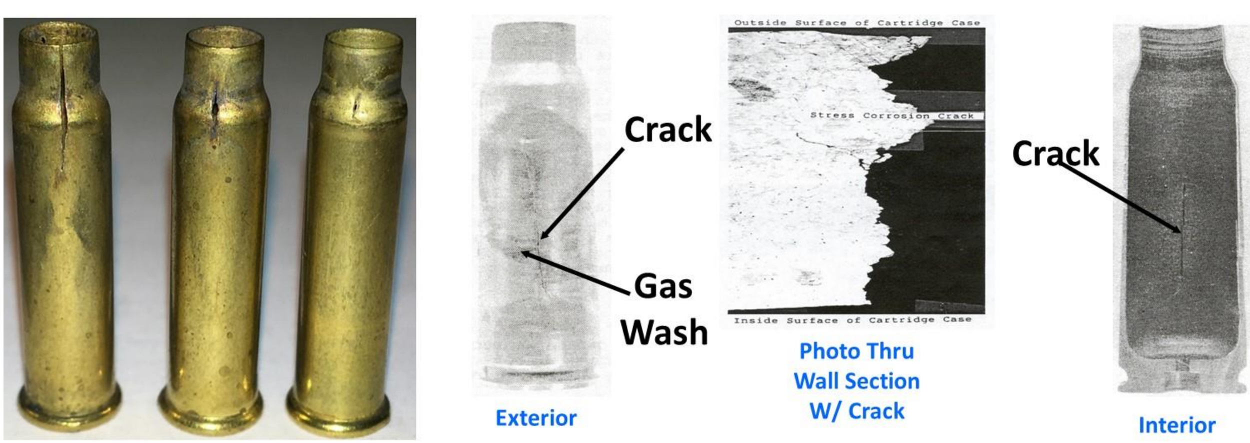

Figure 8: Examples of Stress Corrosion Cracking in Brass Cases

Stress corrosion cracking is initiated at the interior surface of the case because that's where the corrosive atmosphere is located, and the crack will run toward the exterior surface until the stress falls below the level required for propagation. At this point, the crack stops running deeper into the case wall. The exterior of the case looks fine until the cartridge is fired, at which point the crack immediately runs through the case wall to the outside, allowing the case to leak as shown in Figure 8. Generally, the case aft of the crack seals the high-pressure cases in the chamber, preventing unrestricted venting to the atmosphere aft of the case. As a result, these sort of case failures usually do no harm to the weapon provides the cases are brass or steel and there is nothing in the gun mechanism to promote cracking in a preferred location in the chamber.

A condition known as "dezincification" can occur in brass cases; this is where the zinc doesn't stay in solution with the copper with which it is mixed. Dezincification will enhance the likelihood of a case experiencing stress corrosion cracking.

Another failure mode for cartridge cases is one of improper hardness gradient. As mentioned above, both a thickness and a hardness gradient is required for the case to survive peak pressure, unlock and extraction. If the case hardness gradient isn't correct, however, the case can fail at the location where the hardness change is greatest. The left-hand side of Figure 9 shows the upper and lower hardness specifications for the 7.62x51mm cartridge case, along with some examples that function acceptably and one hardness gradient example that results in the case separation failure shown in the right-hand side of Figure 9.

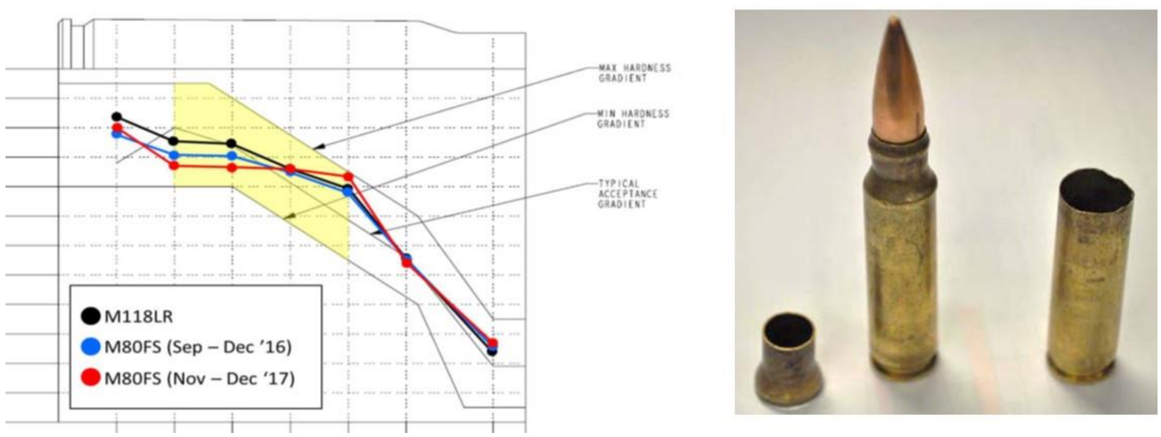

Figure 9: Case Hardness Gradient Spec, Actual and Illustration of Failed Case

See:
https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2019/armament/Krogstad_SA3_3PM.pdf
For more detailed information.

This failure should be of particular concern to hobbyist shooters who are inclined to anneal cartridge case necks and shoulders in their efforts to extend case life or reduce group size because while the process used for annealing can be controlled, testing of the hardness gradient is not something most shooters are capable of measuring. This leaves the shooter with "trial and error" or "shoot to failure" as methods of determining the adequate amount of case mouth annealing.

Lastly, there is the "catastrophic overload" failure of the cartridge case structure. Figure 10 shows a 9mm Luger case (9x19mm) that experienced catastrophic internal pressures. The primer pocket internal diameter should have been 0.210", it was measured at 0.227"; the thickness of the case web on other cases made by the same manufacturer was measured at 0.168", the web thickness of the failed case was measured at 0.122".

Figure 10: 9x19mm Case Exhibiting Catastrophic Internal Pressures

The chamber pressure required to fail the cartridge case, based on a typical hardness profile, was estimated at 95,000 PSI; pressures inside this case are believed to have been well in excess of that. The shortening of the strongest part of the case, the web, the increase in primer pocket diameter and the rupture of the case base, are primary evidence of a significant overpressure event. My thoughts on how this likely happened are the topic of another article.

<u>Other Case-Chamber Interaction Factors:</u>

There are numerous other case-chamber interface factors that affect case and firearm function, some of which aren't controlled by SAAMI/CIP. Among these factors are:

1. Case Hardness Profile
2. Weapon Lock Stiffness
3. Presence of flutes in the chamber

The case hardness profile, discussed above in the case function and case failure sections, is not controlled by commercial interface documents maintained by either SAAMI or CIP. Instead, it is left to the ammunition manufacturers to perform a "function and casualty" test in firearms commonly chambered for the ammunition in question.

The weapon lock stiffness is a measure of the mechanical compliance of the weapon barrel-bolt-receiver load path. The lock stiffness can be determined by testing or analytically with an accurate

3-D model; the load applied to the bolt, divided by the deflection of the bolt relative to the aft face of the barrel is the lock stiffness. The lock stiffness affects the strain the case must survive to provide a reliable seal, but as mentioned above, this parameter is not controlled by SAAMI/CIP. Instead, the previously mentioned “function and casualty” test conducted in weapons commonly chambered for the subject ammunition is a defacto control of this parameter.

Some weapon manufacturers put “flutes” in the chamber of the weapon to reduce the axial stretch of the case during pressurization. By etching longitudinal grooves in the chamber, weapon manufacturers vent a tiny bit of combustion gas back along the forward portion of the exterior of the case, reducing the contact stress between the case and the chamber. This reduces the case stretch in all three directions since it limits load transfer in shear between the case and the chamber in the longitudinal direction. The reduction in between the case and the chamber increases the load that has to be reacted by the bolt. The reduction in case stretch does, however, dramatically reduce the residual load between the case and chamber when the pressure is removed from the inside of the case. This makes the weapon easier to unlock, and the case easier to extract, regardless of the stress-strain properties of the case material. When implementing fluted chambers, the weapon designers have to take the increased bolt load into account when designing the gun lock mechanism. Increased bolt load when employing fluted chambers are the result of the failure of the case to transfer significant load through friction to the chamber at the case-chamber wall interface. Since the case body wall transfers less load in friction to the chamber, the net load transferred to the bolt increases. Figure 11 shows the exterior of a 25x137mm cartridge case that has been fired in a weapon with a fluted chamber. The case neck, shoulder and forward part of the body show the signature of propellant gas vented along the chamber flutes.

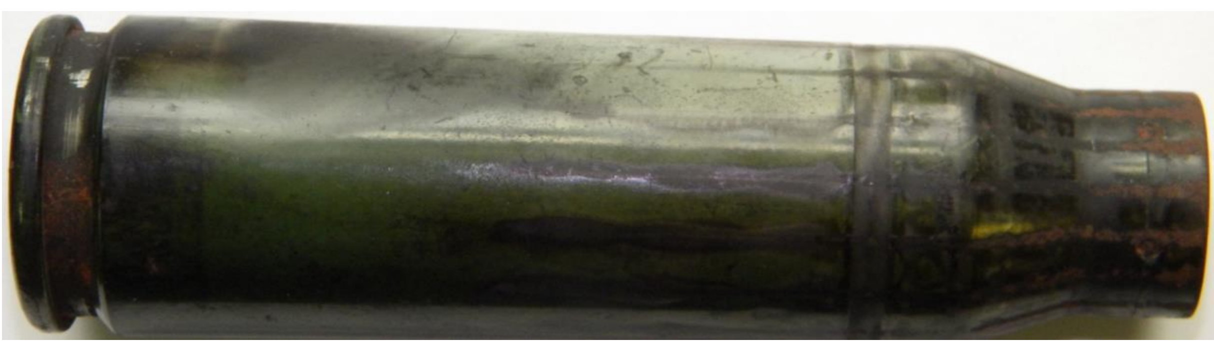

Figure 11: Case Exterior Fired in Fluted Chamber