TECHNICAL UPDATE

Notch Sensitivity of High Strength Metal

Metal Behavior Under Stress

Almost all structures have notches of some kind—threads, scratches, nonmetallic inclusions and corners. Notches cause locally high stresses. A sudden fracture will occur if the alloy cannot stretch to relieve such high stresses. In some cases the failure can be hazardous.

Ductile alloys stretch out of shape in the direction of stress when loaded above the limit of elasticity (somewhat lower than yield strength), thus relieving the stress. If the metal is in a loaded structure of some sort, it may lose its purpose as it loses its shape, but it does not usually generate a hazard; for example, a nail being bent while being driven.

For the common steels, the more ductile alloys have less strength; thus, using them to get adequate strength for a structure requires more space and weight. If less space and weight are desired, higher strength alloys are needed. Unfortunately, the higher strength alloys are most often lower in ductility and may not be able to stretch and relieve stresses around notches without failure.

Metals can be evaluated for their ability to resist such brittle failures. First, machine a notch in the tensile test bar before pulling it. If the notch does not reduce the breaking stress, the alloy is notch tough and can be used at that stress level. If the notch reduces the breaking stress, then the alloy is notch sensitive. The more the breaking stress is reduced, the more notch-sensitive it is. Thus, the ratio of the notched bar tensile strength to the smooth bar tensile strength is a good measure of notch toughness.

Since most parts contain notches, it is not a good idea to use an alloy with a ratio of much less than one for parts with high tensile stresses. This holds true even for parts without obvious notches when made of an alloy in its notch-sensitive strength range.

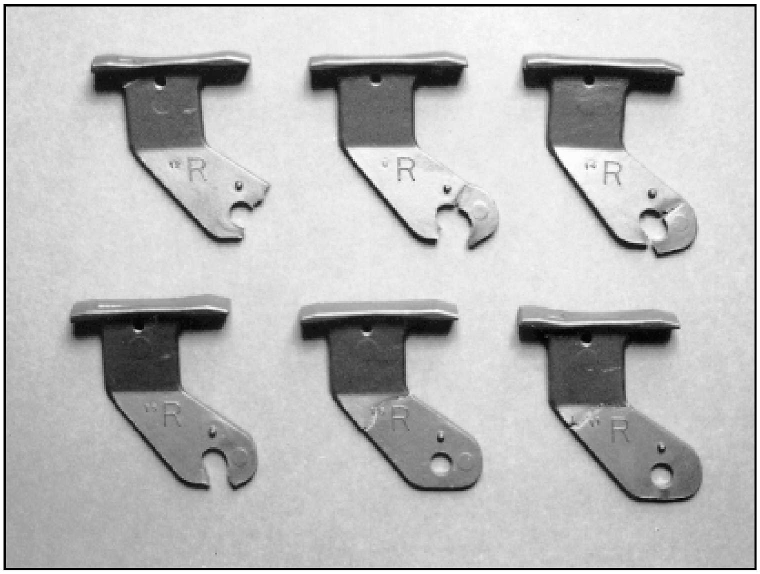


Figure 1. Seat belt sliders studied for casting quality vs. breaking loads

For example, when some gravity cast (ladle poured) 8630 steel seat belt sliders, Figure 1, were heat treated to various hardnesses and tested to failure, the behavior of Figure 2 was obtained. As the parts hardnesses were increased, the breaking load went up at first, but between a Rc of 43 and 48 [tensile strength of 200 to 274 ksi (1379 to 1613MPa)], part failure loads were highly unpredictable, some being lower than at hardnesses of 23Rc [tensile strength of 109 ksi (750MPa)].

The spread in failure loads occurs because the higher hardness steel is more sensitive to small (not detectable by nondestructive testing) discontinuities such as inclusions and metal splatter when the metal is poured. If these discontinuities happen to be located unfavorably to the stress direction, the part fails at low loads. Also, the failure distribution is not normal.

Stress Intensity Factor, K_{Ic}

The stress intensity factor K_{Ic} is a widely accepted measure of notch sensitivity. Because it is a measure of the energy required to propagate a front plane crack through the metal sample, it is an inherent property of the metal tested. This value is sensitive to metal quality, heat treatment, chemical analysis and strength level for a given alloy.

One can calculate the critical crack depth required to start brittle failure in a given metal by using the factor in the equation:

$$a = \left(\frac{Q}{\pi}\right)\left(\frac{K_{Ic}^2}{\sigma}\right)$$

Where:

a = half the crack depth in inches

Q = a shape factor, 0.8 to 1, for the crack

K_{Ic} = fracture toughness, in ksi-in$^{1/2}$

σ = gross stress normal to the crack in ksi

For highly ductile, low-strength alloys, the critical crack depths are too big to be meaningful, even at stresses that are well above yield strength. For a given alloy, K_{Ic} behaves like the failure loads mentioned before, decreasing as the alloy is tested at progressively higher strengths (hardnesses). Critical depths for common alloys at reasonable stresses vary from 0.6 to 0.025 inch and less if the metal is highly stressed. For the same strength and stress level, the critical crack depth can vary from 0.03 to 0.17 inch for different alloys. This variation should be considered when specifying an alloy, its strength levels and nondestructive test standards.

While K_{Ic} helps in understanding why some alloys are better than others, it is difficult to apply in detail for a specific case. For example, Figure 3 shows some breaking load data for the previously mentioned seat belt sliders in different alloys. In this case, the K_{Ic} of the 17-4PH is around 60 ksi-in$^{1/2}$ and the 8630 is around 100. However, the breaking loads of the 17-4PH are higher than the 8630. The better performance of the 17-4PH is due to its higher strength and the fact that it was countergravity (CLA) cast, having fewer minor casting imperfections (Hitchiner Technical Update 2D5). Both the ladle poured and CLA castings have better process capability than the forgings because the forgings are subject to stringers of inclusions and small surface tears, reducing average breaking loads.

Impact Resistance

In addition to notched tensile strength and K_{Ic}, energy absorbed by a sample being broken is another measure of a metal's failure resistance on loading. In this test, a swinging pendulum breaks a bar of 0.394-by-0.394 inch (1-by-1 cm) and the energy absorbed by the fracture is measured. Notching the bar (Charpy V notch) and measuring the energy absorbed at all temperatures of interest for a given part is useful.

Lower temperatures commonly generate lower absorbed energies. In such instances, parts subjected to high loads at those temperatures may show brittle failure. The Charpy V notch sample is used widely to evaluate a metal's brittle failure resistance. When its value is high, the metal is fatigue and brittle failure-resistant. The US Army generated this correlation when evaluating the failures of high-strength gun barrels and established the Charpy impact values for adequate toughness and various strength levels for high-strength, low-alloy steels (Table: Charpy Impact Values). Because Army equipment has to operate at low temperatures, Charpy values were required at the low temperatures.

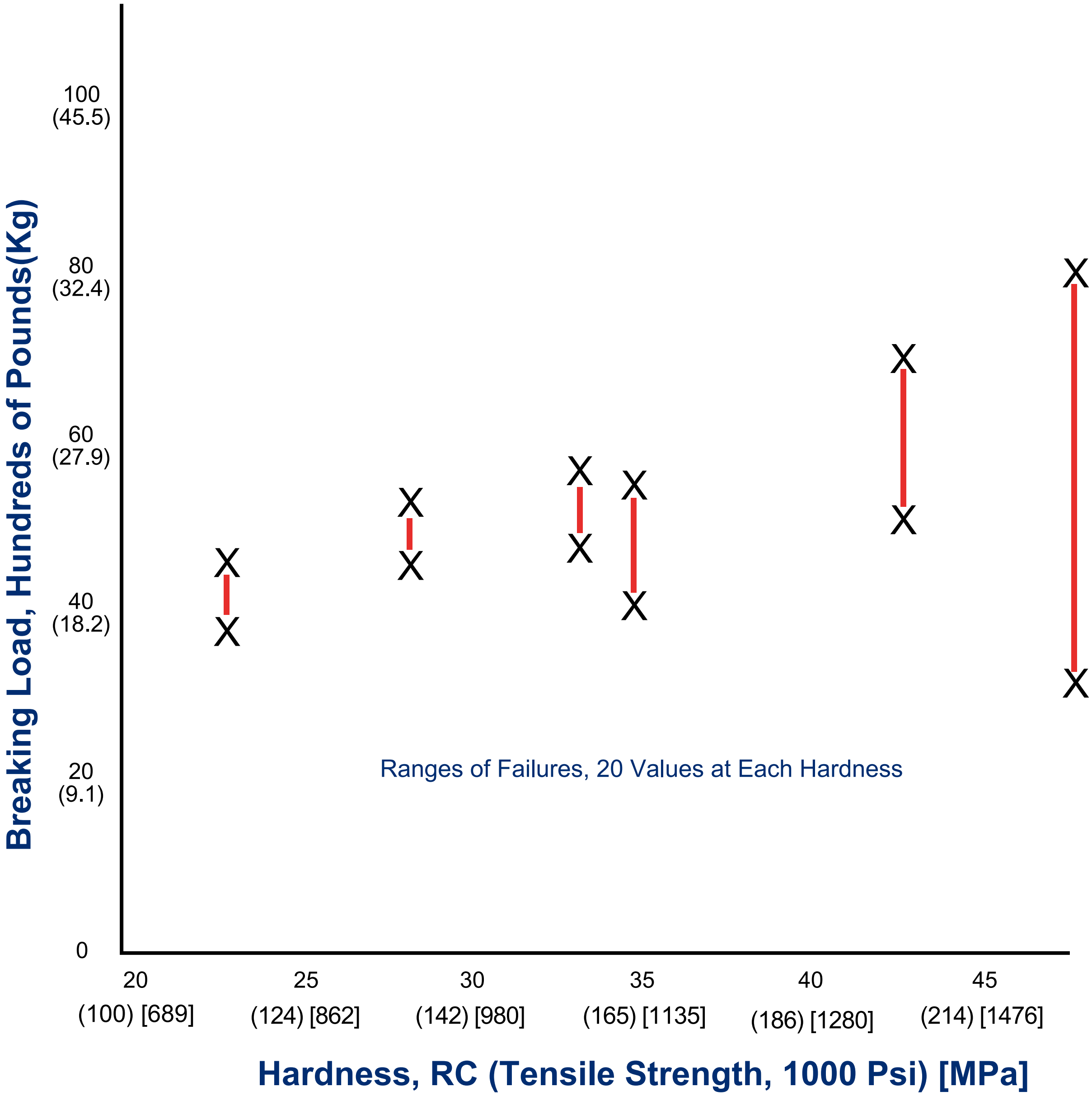
Use of such steels above 150 ksi (1033MPa) requires the foundry to use special techniques to assure adequate toughness. These involve the use of high-purity metals and high-temperature (2500 ºF, 1372 ºC) homogenizing treatments. If this is done, such steels can be used safely at 200 ksi (1378MPa) yield strength. As with the K_{Ic} values, care must be used in selecting one alloy over another by use of Charpy or other impact test value. For example, the strength and impact values of aluminum and magnesium alloys are much lower than low-alloy steels, but, properly used, they can often save weight when used in place of them.

Summary

The real value of all these tests is to assure metal quality control sufficient to achieve the brittle failure resistance level needed for a given part day in and day out. For example, a 5 ft.-lb. (0.7m-kg) Charpy impact energy may be satisfactory for a machine part which must endure sliding friction and wear, but it would be completely unsatisfactory for a golf club head or a pawl for a ratchet wrench. If a part fails in a brittle manner, use one or more of these tests to select a tougher material. If that alloy's performance is adequate, use the tests routinely to evaluate each batch of parts to assure all parts will perform well.

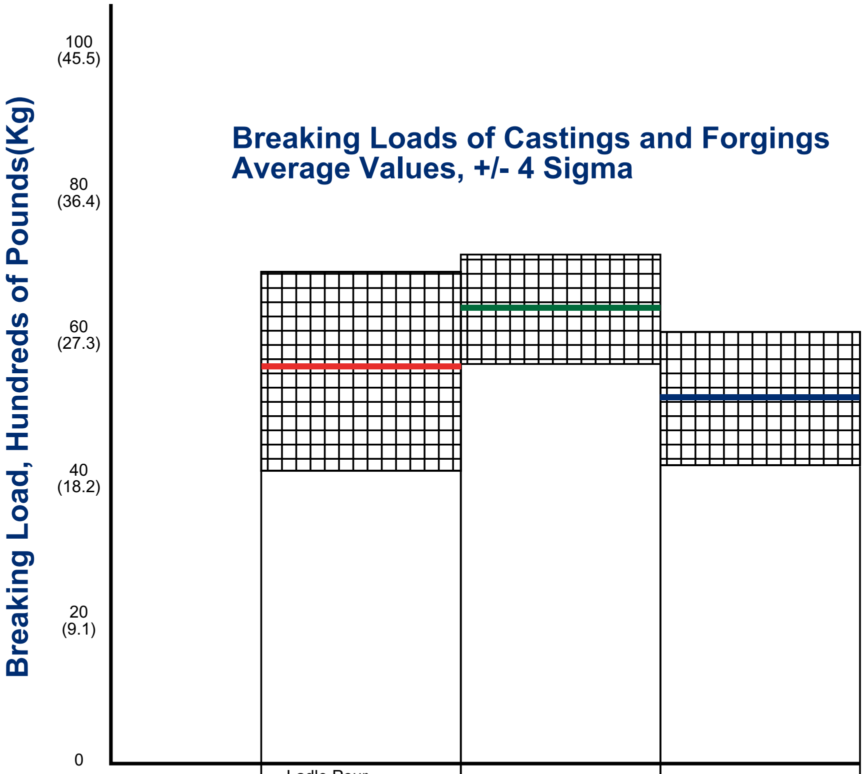
Charpy Impact Values	
Yield strength, ksi (MPa)	**Charpy value, ft.-lbs. (m-kg) at –40º F (ºC)**
100 (689)	30 (4.2)
150 (1033)	15 (2.1)

Table 1



. Failure loads for an 8630 seat belt part versus hardness.

Figure 2



	Ladle Pour 8630 Rockwell 35-40	Cla Cast 17-4ph Rockwell 40-44	8630 Forgings Rockwell 35-40
$\bar{X}$ lbs(Kg)	5422(2465)	6405(2911)	5090(2314)
Normal Population	No	Yes	No
Cpk	2.01	5.25	1.36

Comparison of casting processes with forgings of seat belt sliders. While the countergravity cast(CLA) were the best, both casting processes showed better process capability than the forgings.

Figure 3

HITCHINER MANUFACTURING CO., INC.

Ferrous Division/Gas Turbine Division
P.O. Box 2001
Elm Street
Milford, NH 03055
Tel: (603) 673-1100

Nonferrous Division
P.O. Box 280
600 Cannonball Lane
O'Fallon, MO 63366
Tel: (636) 272-6176

Hitchiner–France
15, rue du Général Leclerc
F78000 Versailles, France
Tel: 01-39-20-07-31

Hitchiner S.A. de C.V.
Cruce de las Carreteras
Tenango-Marquesa y Tianguistenco Chalma S/N
Santiago Tianguistenco, Estado de Mexico
Tel: (713) 3-62-83

Tooling Division
7 Northern Boulevard
Amherst, NH 03031

Metal Casting Technology, Inc.
127 Old Wilton Road
Milford, NH 03055

http://www.hitchiner.com/