The BillaVista 60

Bomb Proof Dana 60
Part 1a- The Tech Behind the Talk
Steel and Material Strength
By BillaVista

The BillaVista-60 Super Dana 60 Front Axle Project.

Go to -->

Introduction

The title of this part, "The Tech behind the Talk", says it all. Part 1a will examine in some detail the subject of "Materials Science", focusing primarily on steel and other ferrous metals. It will attempt to educate the reader on the composition of steel, it's properties and how to properly interpret them, as well as examine the many different types of steel and their uses, and much, much more. As usual, I also hope to dispel some of the vast amount of misinformation that exists surrounding the subject. The purpose of all this is threefold:

1) First and foremost to educate the reader, so that they may be better armed to wade through all of the marketing hype involved with 4x4 products. Armed with this knowledge the reader should be better able to determine for themselves who builds and markets the "best" or "strongest" parts, which manufacturer's really know what they're doing, and who is just "blowing smoke" and trying to capitalize on the latest marketing buzz-words like "alloy", and "chrom-moly".

2) As a secondary goal, I hope to present enough information to assist the reader in selecting material most appropriate for their own construction and fabrication projects, at least within the confines of the disclaimer. At the very least I hope to illuminate the subject enough to motivate the reader to further research or at least begin to ask the right questions.

3) Part 1b is a special section that focuses on a subject that is near and dear to my heart, as well as being one of the least understood yet most frequently asked about topics of all time - axle shaft technology.

Why would I write this, and why should you care?
1) Breaking things sucks!
2) Paying more for something than is necessary sucks!
3) Getting conned by flashy advertising that can't be backed up - sucks!
3) Something not being as safe as it should be, sucks!
4) Misinformation sucks!

It is the intention of this article to address these issues by arming you, the reader, with the ability to calculate where possible, and judge where required, what would be a reasonable material choice for your project, the best material for the parts you wish to buy, etc.

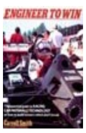
Why steel, in particular?
Simply because, in my humble opinion, it is the greatest material mankind has for construction. It is cheap, strong, readily available, easily cut, joined, and formed. Wood can be light and stiff, but not very strong. The best aluminium is strong and light, but very difficult to join. Titanium is superb in terms of strength to weight ratio and stiffness – but it's incredibly expensive, difficult to obtain, and even more difficult and expensive to machine properly. There's no way you're ever going to perform a battery-weld field-fix on a part made from 7075-T6 aluminium or titanium! In the end – we come back to steel – from mild carbon to some of the more exotic alloy steels – pound for pound it is the most righteous material available for our needs.

Disclaimer

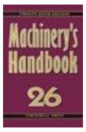
This article is written by the layman (me) for the layman. I am not an engineer, physical chemist, physicist, or metallurgist. Neither am I a machinist, millwright, or certified welder. I am a shade-tree fabricator – just like the majority of you. I can cut, shape, and join metal – subject to the limitations of my limited and non-professional tool collection. All of which is to say – USE THE INFORMATION HERIN WITH CAUTION - AND AT YOUR OWN RISK. This article is not an engineering text, it is not a specific guide to anything – it is background knowledge that you will have to apply yourself, in a manner in which you choose.

Acknowledgements

Throughout this article I have borrowed heavily from many texts, and 3 in particular. I encourage everyone with any interest in the subject to purchase and read these fine books, as they are chock full of excellent information (much more than I can cover here), and well written. They are:



Engineer to Win : The Essential Guide to Racing Car Materials Technology or How to Build Winners Which Don't Break
by Carroll Smith
Paperback - 280 pages (April 1985)
Motorbooks International; ISBN: 0879381868 ;



Machinery's Handbook Tool-Box Edition
by Erik Oberg (Editor), Christopher J. McCauley (Editor), ricca Heald, Franklin Day Jones, Henry H. Ryffel
2640 pages 26 edition (April 15, 2000)
Industrial Press, Inc.; ISBN: 0831126256 ;

High Performance Hardware : Fastener Technology for Auto Racers and Enthusiasts
by Forbes Aird
Paperback - 192 pages 1 Ed edition (April 1999)
Berkley Pub Group; ISBN: 1557883041 ;

Much technical data was also gleaned from the following sites:

http://www.engineersedge.com/

http://www.efunda.com/

http://www.steeltubeinstitute.org/

http://www.emjmetals.com/

http://www.usstubular.com/

I am also greatly indebted to the following technical experts, most of them professional engineers, all of them gentlemen, and valuable members of the Pirate4x4.com forums. Without their selfless sharing of technical facts and information I would never have been able to understand all of this:

Thanks to:

Gordon, PIG, Ed Stevens, Dave Kamp

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Robin Ansell, Goat1 and lt1yj

Outline

Part 1 - The Tech behind the talk is laid out as follows:

Section 1 - Steel basics: what it is, where it comes from, its structure, and why we use it so much

Section 2 - The concept of stress and strain,

Section 3 - The critical definitions - malleability, hardness, toughness, etc.

Section 4 - The steels of interest to us - mild, carbon, alloy steel etc.

Section 5 - Steel manufacturing - alloying, cold rolled, hot forged, etc.

Section 6 - Heat treating and hardness

Section 7 - Design principles - the flow of stress, how removing material can increase strength, shapes are strong, etc.

Section 8 - Fatigue

Section 9 - Dispelling myths / FAQ - hollow vs solid, DOM vs HREW, square vs round, is pipe only for poop?

Section 10 - Equations

Section 11 - Tables

Section 12 - Glossary

Section 13 - Sources and Notes

Section 1: Steel basics

What is steel?

Steel is a metal. The Merriam-Webster online dictionary defines it a metal as:
any of various opaque, fusible, ductile, and typically lustrous substances that are good conductors of electricity and heat, form cations by loss of electrons, and yield basic oxides and hydroxides;

Yea, great – but really – what is a metal, in terms of what we care about? Metals are materials that:

- are able to undergo a large degree of plastic deformation (change in shape) without rupture or failure.
- can be beaten, stretched, pounded, bent, rolled, extruded, molten, cast, and otherwise formed into useful parts.
- are elastic, meaning that, as long as the load is not to great, they can return to original shape and form after an external force or load is removed.
- are also generally strong – that is, they are able to resist failure under high levels of load and stress.

Steel, in my humble opinion, is the king of all metals, having the best of all these properties - especially considering its weight and cost.

So, in summary, steel is a metal that can easily be formed into useful parts, can resist high levels of load or force without breaking, and can change shape (bend) in response to a load and spring back to original shape.

Why steel?

How is it that steel has such wondrous properties? The answer to this question alone could fill several books. I will attempt to give a brief answer, something we can refer back to when we need, in order to help our understanding. My answer certainly won't make metallurgists of you!

As, noted, the reason steel is so strong and yet flexible and formable is very complicated, but the answer all boils down to it's atomic structure and the building blocks this atomic structure leads to, that all interconnect and build on one another until we have the actual steel.

Let me explain a bit further.

Not surprisingly, the answer lies deep within its atomic structure. All I will say here, is that metals are made up of atoms that have strong flexible atomic bonds, lie in very close formation and that are arranged in a regular and repetitive fashion into crystal unit cells of various shapes which are, in turn, built up, Lego-like, on a regular and repetitive 3-dimensional lattice structure into crystals of metal called “grains”. The nature of these atomic bonds, and the resulting crystal lattice structure, is what lends metals, and particularly steel, it’s combination of strength, hardness and malleability. **In a gross over-simplification, we can say that steel atoms bond and form crystals, small crystals, or "grains" of metal join together to form a crystal lattice structure, much like bricks join together to form a wall.**

Continuing our brick wall analogy: the nature of the crystal lattice structure - i.e. how regular the grains are in shape and orientation - determines the properties (and chiefly of interest to us, the strength) of the metal. In much the same way as the shape and orientation of the bricks in a wall determine the properties or strength of the wall. Compare an old-fashioned stone wall constructed from stacked boulders and stones to a modern wall of precisely arranged rectangular concrete blocks.

There are many factors that determine the size, shape, and orientation of the grains and crystal lattice structure, many of which we can manipulate. It is these factors and their manipulation which really interests us. The factors range from the atoms themselves i.e. the composition or "alloy" of the steel, to the shape and orientation of the grains - affected by things like forging, heat treating, cold working etc.

One more brick-wall analogy: The bricks, their size, shape, and orientation to one-another determine not only how strong a wall is - but also in what way it is strong. For example, an old fashioned rock wall may have a great deal of strength if we bear down on it from above - i.e. set something heavy on it and it will easily support the load. However, lean against it sideways and it may easily topple over. In much the same way, the different ways in which we manipulate and treat steel can impart many different properties or "strengths" from compressive strength to shear strength - more on this later.

Ultimately, it's all in the atomic and inter-atomic bonds. How we forge the steel from ore, what alloying elements we add to it, how we "work" it, and even how we machine and weld the final product will all have an impact on the atoms/grains/crystal lattice structure - and therefore strength and properties of the steel. Understanding how this happens and why is chiefly the goal of this article.

As a point of trivia, there is no such thing as a “molecule” of steel. In fact, metals, as a family of elements, are distinguished from other elements in part because their crystalline structure is made up of individual atoms (they are monatomic) as opposed to molecules.

Where does steel come from?

Steel is not a naturally occurring substance - it is entirely man made. Steel is chiefly a combination of two naturally occurring elements: iron and carbon (along with small amounts of other elements - depending on the steel in question). The process by which man makes steel, would, again, fill several volumes. Here is my amateur synopsis:

Iron is mined from the ground in the form if a reddish-brown rock called iron-ore. This ore is then smashed up, strained, filtered, chemically treated etc, until ultimately it is melted in huge blast furnaces into something called pig iron. The process uses coke (a type of coal), which in turn imparts large amounts of carbon to the pig iron. As a result, pig iron itself is full of impurities, brittle, and unmachinable - practically useless. Except - it is the raw material from which all other irons and steels are made. Pig iron is so produced in either huge vats of molten material, or it is cast into ingots (in fact, pig iron got it's name because the ingots or "chunks" produced were thought to have resembled piglets).

Pig iron is then refined into either metallic iron or steel using specialized furnaces and processes. The distinction between the two is that metallic iron has between 2-6% carbon content, and steel has <2% carbon content. Of course metallic iron is further refined into, and categorized as, many different types of iron - from grey cast iron to nodular iron; in much the same way as steel is further refined into and categorized from low carbon steel to alloy steel. We'll explore all of these in detail later. Metals like iron and steel, being largely composed of elemental iron, are known as "ferrous" metals after the chemical symbol for elemental iron - Fe.

A final word about carbon. carbon is critically important to our whole discussion because **it is the presence of carbon that turns the element of iron that is naturally soft and weak, into the strong, rigid materials we know as iron and steel.** Precisely how this is so is beyond the scope of this article, suffice to say:

The strength, hardness and toughness that make the ferrous based metals useful to us are profoundly influenced by the remarkable sensitivity of the physical and chemical properties of iron crystals to relatively small percentages of carbon dissolved within their matrixes (actually, the sensitivity is to the movement of dislocations within the crystal space lattice). This sensitivity to dissolved carbon is in fact, the very basis of ferrous metallurgy. [1]

A poor, but perhaps useful metaphor may be the use of fibre-mat and resin in fibreglass work. The bulk raw material of fiberglass is the fibre matting (as iron is to steel) - but by itself the matting is of no practical use. Not until we add the resin to it to make fibreglass (as we add carbon to iron to make steel) do we get a useful product. In both cases, neither raw material is much use alone, but combine them and we really have something. Similarly, though carbon may only be present in small quantities, just as the amount of hardener added to fibreglass resin has a profound effect on the material, so does the small amount of carbon present in useful metallic iron and steel.

Section 2: Stress and Strain

You may have noticed that we have already bantered around a bunch of terms that we really should define - just so we're on exactly the same page. And there's many more terms to come. So lets lay out some initial definitions now.

Strength - a measure of how strong something is! ha ha! Seriously, this is a very important definition, as this entire series of articles is, in large part, just about how strong things are. Not only that, but the truth is not nearly as simple as my little joke above would lead you to believe.

In the broadest of terms, when we speak of a substance or products strength, we are talking of it's ability to resist an external force or load, without deforming, breaking or rupturing. Technically we say a materials **strength is the greatest stress it can endure without rupturing** (by rupturing - I mean the atomic bonds coming completely apart.)

There are many specific kinds of strength, from the "pure 3" - tensile, compressive, and shear to complicated combinations such as torsional and bending. We will examine each of these in detail throughout the article.

Stress. We all know instinctively that, generally speaking, if we have 2 things made from the same stuff, that the larger will be "stronger". In order for us to be able to discuss the strength of material, and particularly to compare different materials, we need a way to compare strength without constantly referring to how big something is. That is, we need to be able to eliminate size as a factor. We do this by employing the concept of stress. **Stress is a force or load applied, divided by how big the part is**, in other words force per unit of cross sectional area. It is common to measure the force applied in pounds and the cross sectional area in square inches. Thus, the unit for stress is pounds per square inch, or PSI

Using the concept of stress, we can now compare relative strengths regardless of size. Say we have 2 steel bars, one is 1 square inch in cross sectional area, the other 1/2 sq. in. If they are both made from a material having a breaking strength of 10,000 psi, one will break when 10,000 lbs is applied, the other when 5,000 lbs is applied, despite that they are made from the same material. Conversely, if we have 2 products of unknown or difficult to determine size but we know that one is made from a material with a yield strength of 75,000 psi and the other 100,000 psi, we know that the second is made of a stronger material (regardless of comparative size), and we can also say that the first would have to be 25% greater in size to be of equal strength. This logical approach can lead us to quite accurately determine that, if the sizes are similar, the second is definitely the stronger product.

Strain - closely allied to the concept of stress - the concept of strain allows us to quantify or describe how a part or material responds to an applied force or load. Quite simply: **Strain is a change in shape or dimension in response to a stress**. It is usually expressed in percent elongation (%) Percent elongation is the difference in length between the original length of a test specimen (often 2" in length) and that same specimen after it has been ruptured by a tension load.

In other words, materials STRAIN to resist a STRESS (much like people do to!).

Stress and strain are two separate, useful concepts but the real power of these concepts is only realized when the 2 concepts are combined. **There is a defined relationship between stress and strain, discovered by an English bloke in 1680, that states the strain of any material is proportional to the stress within it. It is known as Hooke's law and is simply stating what you already know – "the harder I push on this, the more it will bend……". What's important though, is that, up to a point, this relationship is proportional, or linear…meaning that if I push twice as hard, it will bend twice as far. The point up until which this is true is called the elastic limit. Realize that Hooke's law applies not only while a load (stress) is applied, but also when it is removed. Meaning, as long as we are within the elastic limit of the material (i.e. the stress is less than the elastic limit of the steel) strain is always proportional to stress, meaning if stress (load) is zero then so too is strain (distortion). What we have just described is one of the most righteous properties of steel. That is, it is "elastic" in nature - which is a fancy way of saying: up to a point, we can bend it by applying a load, then if we remove the load it will "spring" back to exactly the same shape and size it was originally. We call this elastic deformation. Of course, we can apply a stress that exceeds the elastic limit of the steel, and if we do, the steel changes from elastic in nature (able to spring back) to plastic in nature - meaning the stress applied, once it passes the elastic limit, will result in a permanent change in shape of the metal. This we call plastic deformation.** Another quote from Mr Smith is in order:

A solid is considered to be elastic if, after a change of shape due to an external load, the body returns to its original size and shape when the load is relaxed. Plasticity, in the metallurgical sense of the word, is the ability of a metal to be deformed beyond its range of elasticity without fracture; the result is a permanent change in shape. These two related properties are the most significant of all the characteristics of the family of metals. Plasticity gives us the ability to form metals into useful shapes and elasticity allows us to use metal fabrications as load-bearing members in our structures. [2]

You can begin to see now, how with a little knowledge, and an idea of the stress/strain diagram we can solve forever the arguments of whether something is stronger than something else, whether it is "too brittle" or will "bend before it breaks" etc.

Let's examine a sample, theoretical graph of stress vs strain, called a stress/strain diagram

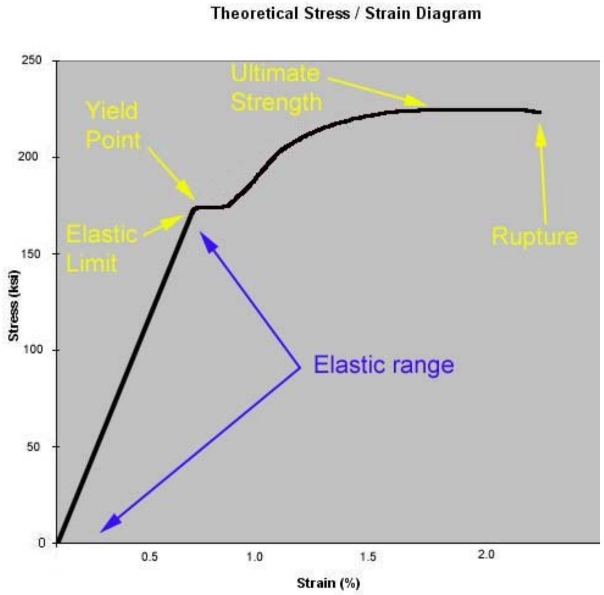


*Diagram concept adapted from "High Performance Hardware". Forbes Aird; Berkley Pub Group, 1999 p.14

There are a few important concepts to note here:

- This is an example only, the numbers are not meaningful, and the slopes have been hugely exaggerated for illustrative purposes.
- Note the straight line portion, the "elastic range" of the metal (indicated by the blue arrows). This is the region where stress and strain are directly proportional - hence the straight line. Remove the stress, the strain disappears too. If this were a real metal, any load below about 170, 000 psi can be born without permanent shape change.
- Note the elastic limit - The point on the stress-strain curve beyond which the material permanently deforms, even after after the stress is removed
- Note the Yield Point - this is the point at which a material exhibits a strain increase without increase in stress. There is a subtle but important distinction between the yield point and elastic limit, that we can see if we observe the horizontal line between the elastic limit and the yield point. We can safely stress something to the elastic limit, but once we reach the yield point, it is already too late - even if we add no more stress, strain will continue to increase. You can illustrate the concept by pulling on a piece of taffy or warm plastic or even play-dough. Pull on it gently but increasingly harder, at some point stop increasing how hard you pull and just maintain a constant pull: if you pulled hard enough (equal or greater than the yield point) even though you stop pulling harder, it will continue to stretch and still come apart. At the yield point a material has exceeded its elastic limit and becomes permanently deformed.
- It is one of those "facts of life" that the elastic limit is of great interest to us, but that it is very difficult to accurately measure a materials exact elastic limit. Because of this we have the concept of "yield strength". The yield strength (not to be confused with yield point) is stress at which a material exhibits a pre-determined, standard amount of elongation (strain). The usual standard is 0.002" of elongation per inch of original length, or strain of 0.2%. Ultimately, in practical use, we generally use the materials yield strength to describe its approximate elastic limit, and can do so reasonably safely since the 2 values are, in reality, so close that they are practically interchangeable. We should never be designing that close to the limits anyway.
- Note that the highest point on the curve describes the ultimate strength of a material. This is the maximum stress a material can withstand without rupture or failure. It is calculated by dividing the load at failure by the original cross sectional area.
- Note that one can apply a stress higher than the yield point, up to and including the stress at the ultimate strength, and still the material will not rupture. But because the yield point has been exceeded, there will be a permanent deformation - illustrated by the fact that the graph is a curve at any point past the yield point.
- Note that there is a defined rupture point where the curve stops. This is the amount of deformation at which the material actually rips apart or ruptures. How far to the right this point is, is an important part of the overall picture of the materials' properties.
- Note that the total area under the curve represents the total of all possible stress and strain combinations where the metal has not yet ruptured. As such, it is an indication of the materials "toughness", toughness being the ability of a metal to absorb energy and deform plastically before fracturing

Comparative stress/strain diagrams

Now that we have a good idea of all that the stress/strain diagram illustrates, it is extremely educational to examine some comparative stress/strain diagrams.

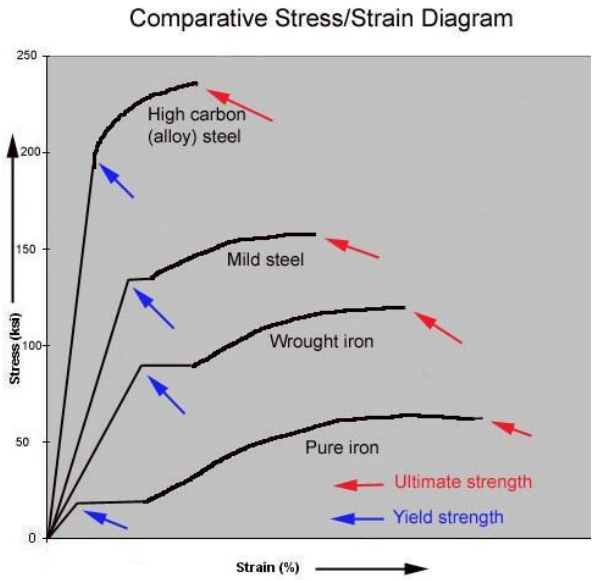


*Diagram concept adapted from "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.41

Examining this diagram carefully, we can learn much about the properties of different materials, and ultimate ly that materials suitability for a given part.

Note: Again, this diagram is for illustrative purposes, the actual scale of numbers used are not real, but are for illustration only - the relative shape and size of the curves between the different materials is real however. It is the concepts that are important.

A good understanding of what is really going on here can help us understand much of the "common wisdom", as well as the persistent myths that are out there regarding steel and iron parts - from the "grade 8 bolts are too brittle" nonsense to other commonly held misconceptions about cast iron and steel.

The differing yield strengths of the different materials are indicated by the blue arrows, and the ultimate strengths the red arrows.

Note:

- Pure iron yields under such low stress that it is of no practical use in constructing load bearing parts.
- That the longer the curves (from left to right) the more ductile the material - the more it can deform without rupturing BUT keep in mind the relative yield strengths. Remember - Once a material has "yielded", it has exceeded its elastic limit and will never return to original shape/size - it has permanently deformed and so in almost every case must be considered to have failed and requires replacement.
- **Notice the vast differences in the stress a material can stand before yielding. Wrought iron may have a long curve, and therefore be able to deform substantially before rupturing, but yields at such a low stress that it is not a very good choice. In contrast, high carbon steel may rupture comparatively soon after having yielded (the curve is shorter left to right), but it doesn't yield until subjected to such a far greater stress than other materials that it is actually much stronger.**
- **As well as noting the length of the curve left to right (elongation, or deformation) between yield and rupture, note also the vertical distance in stress between yield and rupture. Note that the softer, weaker materials rupture after a comparatively small increase in stress since beginning to yield, while the stronger materials, such as alloy steels, can tolerate a much greater increase in stress between beginning to yield and rupturing.**

These last 2 points are the root of what I see as one of the most often misquoted and most poorly understood concepts of material strength - the interrelationship between ductility and strength.

Take for example the classic misconception/myth: "Grade 5 bolts are a better choice than Grade 8 because the grade 8 are too brittle and will snap, while the grade 5 will bend before breaking".

By examining the above stress/strain diagram and imagining the grade 5 bolts represented by the "mild steel" curve and the grade 8 bolt by the "alloy steel' curve (accurate enough for our purposes) we can clearly see both the underlying "truth" in the myth, as well as the great error that ultimately leads it to be an incorrect statement and a very poor guide for bolt choice in all but a very few cases.

First the "truth". We can see from the curve, that indeed, the grade 5 bolt will deform more (exhibit greater strain) between yield point and rupture. However, the myth neglects two critical factors that become abundantly clear when looking at a stress/strain diagram:

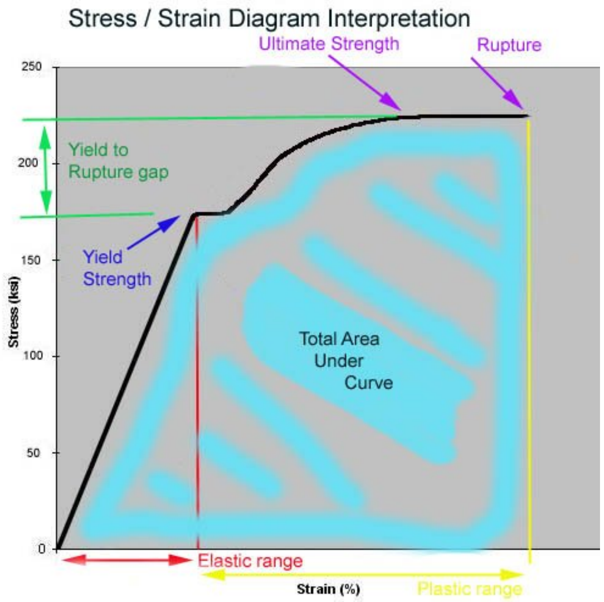
- The yield point of the grade 8 is MUCH higher than the grade 5 bolt. Sure the grade 5 bolt will bend before breaking, and proportionally more than the grade 8 - but it will have yielded, bent, and ruptured long before the grade 8 bolt has even approached yield strength.
- The vertical distance (stress or load increase) between the yield strength and the ultimate strength of the grade 8 is much greater than the grade 5 - meaning that, while the grade 8 may not bend much before breaking - it will tolerate a much greater increase in load between beginning to yield and rupturing. In contrast - the grade 5 will begin to yield, and then it will take very little additional stress (load) to make it bend a whole lot more, and eventually break.

And finally, one more kernel of "truth" to the myth. The one place the grade 5 may be superior is in the area of "impact strength" or "toughness". By impact strength we mean the ability to withstand a sudden impact or shock load. An example might be when a snowplow running through powder at 30 mph suddenly hits an 8" concrete curb (ouch!) The loads imposed by such a sudden impact are exponential, off the chart, and hard to calculate or predict accurately. Remember that we said that the total area beneath the curve is an indication of the materials toughness, and that toughness was the ability to absorb energy? This ability to absorb energy is exactly what we need in the case of a severe impact shock load, and we can see that the area beneath the "grade 5" curve is greater than beneath the "grade 8" curve. Having said that though - the grade 5 bolt subjected to a shock load is ONLY a better choice because it may allow you to limp home without the plow (or whatever) separating from the truck - the bolt will almost certainly still have passed the yield point and has technically "failed" and therefore requires replacement.

This case study is but one example of how we can apply a true and accurate understanding of materials, specifically stress/strain diagrams, to either our own part fabrication or our judgement of which part is really "strongest", "best", or "most suitable".

Essentially, the choice of a material for any given structural duty or load bearing part boils down to a considered compromise or trade off between how high and steep the curve is (the yield strength) and how long it is (how much it can deform before rupturing), and the height between yield and ultimate strength (how much more stress it can take since yielding before rupturing)

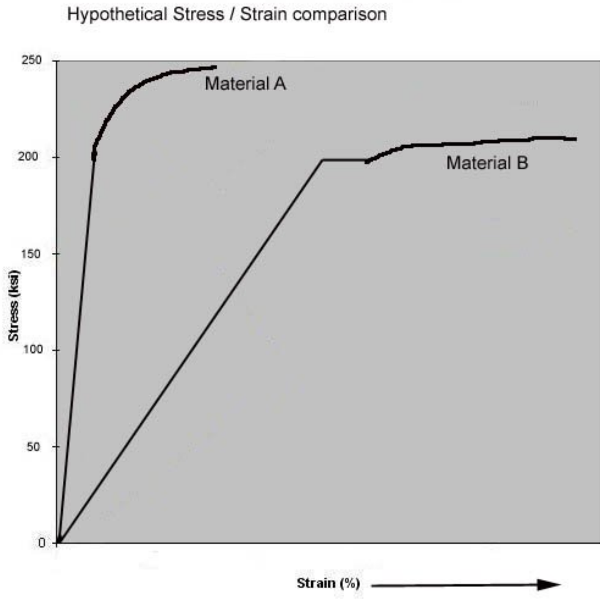
Ultimately, we can label a stress/strain diagram slightly differently to help us understand the qualitative and quantitative differences between different materials. I have chosen to do so like this:



- The yield strength (blue arrow) describes the stress at which the material begins to deform permanently - safety factors not withstanding, it is the maximum load the part should ever see.
- The elastic range (red arrow) indicates how much the part can be loaded and still spring back
- The Elastic Range +Plastic Range (red + yellow arrows), or total curve length indicates how ductile the material is - how much it can deform without breaking
- The total area under the curve (light blue shading) indicates how tough the material is - how much energy it can absorb while deforming plastically and not breaking
- The yield to rupture gap (green arrow) indicates how much more load a part can take after it begins to yield, before it breaks.

One final point - remember - it is the whole stress/strain curve that really describes how a material will react under load - the size, shape, etc. - NOT just any singular value (this, in fact shows the fallacy we indulge in when we blithely compare products by quoting just a single property - like ultimate tensile strength or the like). Compare, if you will, the following 2 curves for 2 different, completely hypothetical materials. Note from the curves that, though they share very similar values in yield strength and even similar ultimate strength, they are VERY different materials and will react under load in very different ways - making them potentially much more or less suitable for any given use.

Study the diagram, and once you completely see and understand this, you are ready to proceed, young grasshopper!



Section 3 - The Critical Definitions

Now, it would be impractical for us to try and communicate about different materials and parts simply by comparing stress/strain diagrams, despite the great amount of information they portray; not to mention how complicated it is to collect the data to plot an actual graph. As such, we have a whole vocabulary surronding metal parts that we use to describe the properties of various steels, and the parts made from them. Here are some of the most important definitions. Note how they can all be derived from, illustrated by, or relate back to the stress/strain diagram.

Hardness – is the property of resisting penetration. Normally, the hardness of steel varies in direct proportion (i.e. as one gets bigger so does the other and vice versa) to its strength – the harder it is, the stronger it is, and vice-versa.

Brittleness – is the tendency of a material to fracture without changing shape. Hardness and brittleness are closely related. The harder (and therefore stronger) a metal is, the more brittle it is likely to be. Materials that are too brittle will have very poor shock load resistance.

Malleability – is the opposite of brittleness. The more malleable a material, the more readily it can be bent or otherwise permanently distorted. As hardness was closely related to strength, so then is malleability. Generally, the more malleable a metal, the weaker it is.

Ductility – much like malleability, ductility is the ability of the material to be drawn (stretched out) into thin sections without breaking. The harder and stronger a metal is, the less ductile, and vice versa.

Toughness – The ability of a metal to absorb energy and deform plastically before fracturing. It is usually measured by the energy absorbed in an impact test. The area under the stress-strain curve in tensile testing is also a measure of toughness.

You can see how there is a trade-off between a metal's malleability/ductility and its hardness/strength (which makes perfect logical sense – since malleability is the ease with which we can form it, by applying force, and strength is its ability to resist force). There are a whole group of people employed in a field called "physical metallurgy" whose job it is to figure out how to use things like alloying, heat treatment, and cold-working to skew this relationship (malleability/strength) in our favour, so that hopefully we can develop materials that are both strong and malleable. It will, of course, come as no surprise that their best efforts cost the most money - aint it always the way! We'll be looking at what they've come up with so far in a little while.

Before we begin our examination of specific steels and treatments, there are a couple more principles we need to get under our belts - the modulus of elasticity and the concept of stiffness.

Modulus of elasticity and the concept of stiffness.

Intuitively we all know that load bearing parts must be strong, must be built from material that is strong. But there is more to it than that. We already defined **strength as the greatest stress a material can endure without rupturing.** But that's not all - for given just that definition - we could decide to build load bearing parts out of soft materials that are strong - like copper and rubber - they can tolerate large loads without rupturing. However, we know instinctively they wouldn't be suitable for building bridges, buildings, crankshafts, frames and axles - they are too flexible and while not rupturing under the load - they would deform too much. **So - what we need is a material that while strong, will also resist deforming under load - we call this property STIFFNESS. We need load bearing parts made from strong (so they don't break) and stiff (so they can bear the load without excessive deformation) materials.**

How do we determine what materials are suitably "stiff" as well as being strong? The problem is complicated by the fact that how stiff something is, is a function of not only the material, but also the shape. For example, take a piece of paper - not very stiff is it? Now roll it into a tube and press it together lengthwise - pretty stiff eh? In much the same way as we use the concept of stress to isolate strength due to material from strength due to size; so we need a way to isolate stiffness due to structure (shape) and stiffness due to material. Another English guy figured it our for us. In 1800 English physicist Thomas Young discovered that he could rewrite Hooke's law to read **"for any material, stress divided by strain is equal to a constant"**. What this deceptively simple statement hides is the very fabric of all structural design engineering - namely that **elastic materials, such as steel, all have a unique "constant of elasticity" that describes the materials elasticity - it's ability to spring back into shape after a stress is removed. This constant of elasticity is a measure of how stiff the material is - the larger the constant, the larger the stress than can be applied without exceeding the elastic limits of the material, and the stiffer the material.**

This "constant" is unique and constant for each material, and is known as the Young's modulus or the "modulus of elasticity" of the material. In order to be able to compare materials, in much the same way as there is s standard way to measure yield strength (stress required to produce 0.2% elongation), there is a standard way to calculate Young's modulus. Young's modulus is defined (and calculated) as the the stress required to double the length of a test specimen. Obviously this is a theoretical value, useful only for comparing materials stiffness, as no structural material on earth can actually be doubled in length without rupturing. **The modulus of elasticity for all steels is about 30, 000, 000 psi !!!!**

Stop! Read that again! Yes, that's right - the modulus of elasticity is the same for ALL steels. This means they are all comparably stiff, they will ALL resist bending or twisting about the same amount - from cheap pipe to expensive cr-mo tubing. The difference between them is what happens when they bend - in other words, the stress/strain curves are different. The better, more expensive steels, due to their much higher yield points and greater elastic ranges, will be able to easily shrug off the load, wheras the lesser material may yield (take a permanent set, or bend) or actually rupture. This is very important, and hugely misunderstood concept, so I'll repeat it. **All steels will bend or twist the same amount under the same load - the difference is in how they handle this loading - good steel will "spring back", poorer steel will bend permanently or break.**

Mathematical proof of this comes from the equation used to determine how much a tube will deflect under a given load. The equation is:

P*L / (E*I)

where:

P = the load (force) placed on the tube (lbs)
L = the length from where the tube is supported to where the load is applied (in)
E = modulus of elasticity (same for all steels)
I = Moment of Inertia.

In comparing 2 tubes, the only factor in this equation that can change is the Moment of Inertia, I

The formula for calculating I for any tube is:

I = (0.049*OD^4) - (0.049*ID^4)

Where:

OD = the outside diameter of the tube
ID = the inside diameter of the tube

Note that the equation does not take into account anywhere the type of steel the tube is made from. The factors that effect how much the tube will deflect, or bend, are just the OD and ID of the tube (or OD and wall thickness if you prefer, it amounts to the same thing); with OD being the much more powerful determining factor.

Now, you might reasonalby ask - why build anything of expensive steels then? Where are the equations to deal with that? Remember, the tube will deflect the same amount, but whether it survives that deflection is where we get into the difference between steels, using the concept of yield strength.

How much load the tube can handle before yielding (changing shape permanently) is calculated as:

Ld = 2*I/OD*Fy/L

Where:

I = I = Moment of Inertia
OD = the outside diameter of the tube
L = the length from where the tube is supported to where the load is applied (in)
Fy = the yield strength of the steel in question.

This last factor, Fy, is where the different steels will have hugely different values - from 30,000 psi for A-53 welded pipe to 240,000 psi for quenched and tempered 4340 Cr-Mo tubing.

I should point out that these equations are shown simply for the purpose of understanding and illustrating the concepts discussed: **DO NOT USE THEM for calculations**, as they may not include critical elements such as design factor, impact loads, safety margins, and fatigue factors! (that's what professional Engineers are for :-)

Mr Smith summarizes quite nicely:

"*We do not build structures from materials with low moduli of elasticity* [non-stiff, flexible] *simply because such structures would sag under any reasonable load...We do not make structures from weak materials simply because such structures would break under load. Together the two properties of stiffness and strength define the physical properties of a solid material. For instance:*

- *Steel is strong and stiff*
- *Copper is strong and flexible*
- *Fibreglass is weak and stiff*
- *Lead is weak and flexible"* [3]

And finally, before moving on to the next section, we shall now cover some of the other more commonly encountered and more important definitions. Other definitions are covered in the glossary:

Alloy The mixture of any element with a pure metal. However, there are several elements regularly occurring in plain carbon steel as manufactured, such as carbon, manganese, silicon, phosphorous, sulphur, oxygen, nitrogen and hydrogen. Plain

carbon steel is therefore an alloy of iron and carbon and these other elements are incidental to its manufacture. Steel does not become alloy steel until these elements are increased beyond their regular composition for a specific purpose, or until other metals are added in significant amounts for a specific purpose.

Alloying Elements
Chemical elements added for improving the properties of the finished materials. Some alloying elements are: nickel, chromium, manganese, molybdenum, vanadium, silicon, copper.

Alloy Steel
Steel is considered to be alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: Manganese 1.650/0, silicon,.60%, copper,.600/0, or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy. Steels: Aluminium, chromium up to 3.9~, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect.

Carbon Steel
Steel is classified as carbon steel when no minimum content is specified or required for aluminium, boron, chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium, or any other element added to obtain a desired alloy effect; when the specified minimum for copper does not exceed .40% or when the maximum content specified for manganese does not exceed 1.650/0; silicon .600/0; copper .60%.

Cold Finishing
The cold finishing of steel, generally used for bars and shafting, may be defined as the process of reducing their cross sectional area, without heating, by one of five methods: Cold rolling, Cold drawing and grinding, Turning and grinding, Cold drawing, or Turning and polishing.

Cold Rolling (Cold Finishing)
A forming process in which metal is rolled or drawn through dies, usually at room temperature. This produces a product with certain advantages over hot rolled steel, such as tighter tolerances, increased properties, improved finish and straightness.

Ductility
The ability of a material to be plastically deformed without fracturing

Elastic Limit
The greatest stress which a material is capable of developing without a permanent deformation remaining upon complete release of the stress.

Endurance Limit
Also known as fatigue limit, a limiting stress, below which metal will withstand without fracture an indefinitely large number of cycles of stress. If the term is used without qualification, the cycles of stress are usually such as to produce complete reversal of flexural stress. Above this limit failure occurs by the generation and growth of cracks until fracture results in the remaining section.

Fatigue
The phenomenon of the progressive fracture of a metal by means of a crack which spreads under repeated cycles of stress.

Fatigue Resistance
The ability of a metal to withstand repeated and varying loads.

Ferrous
Metals or alloys that contain appreciable amounts of iron.

Forging
A hot working operation generally involving plastic deformation of metal at high temperatures into desired shapes with compressive force.

Fracture Toughness
The ability of a material at a given temperature to resist further crack propagation, once a crack has started.

Hardness
The ability of a metal to resist penetration, defined in terms of the measurement (Brinell, Rockwell,Scleroscope, Vickers, Knoop etc.)

Hardenability
This relates to the ability of steel to harden deeply upon quenching and takes into consideration the size of the part, the method of quenching and the analysis and grain size of the steel. Carbon steels are considered as shallow hardening and various alloy and tool steel grades are considered deep hardening or through hardening.

Hardening
Increasing the hardness by suitable heat treatment, usually involving heating and cooling. When applicable, the following more specific terms should be used: age hardening, case hardening, flame hardening, induction hardening, precipitation hardening, and quench hardening.

Heat Treatment
An operation or combination of operations involving the heating and cooling of a metal in the solid state for the purpose of obtaining certain desirable conditions or change in properties or metallurgical structure. Heat treating operations include annealing, normalizing, quenching and tempering, etc.

Hot Rolled
Hot rolled products are those products that are rolled to finish at temperatures above the recrystallation temperature.

Impact Toughness
The ability of a material to resist fracture under an impact.

Mechanical Properties
The properties of a material that reveal its elastic and inelastic behaviour where force is applied, thereby indicating its suitability for mechanical applications; for example, modulus of elasticity, tensile strength, elongation, hardness and fatigue limit.

Modulus of Elasticity
Measure of stiffness. The ratio within the limit of elasticity of the stress to corresponding strain. The stress in pounds per square inch is divided by the elongation in fractions of an inch for each inch of the original gauge length of the specimen. The modulus of elasticity for cold rolled steel is 29,500,000 psi and for other steels varies between 28,600,000 and 30,300,000 psi.

Plastic Deformation
Deformation of a material that will remain permanent after removal of the load which caused it.

Quenching
A process of rapid cooling from an elevated temperature by contact with liquids, gases or solids.In the heat treating of steel, the step of cooling metals rapidly in order to obtain martensite by immersing or quickly cooling the steel in a quenching medium. The quenching media may be water, brine, oil, special solutions, salts or metals; and the intensity of the quench is determined by the temperature, volume and velocity of the media. In the case of air hardening tool steels the quenching medium is air at room temperatures.

Residual Stress
Macroscopic stresses that are set up within a metal as the result of non uniform plastic deformation or thermal gradients. Stresses of this nature are caused by cold working or by drastic gradients of temperature from quenching or welding.

Rockwell Hardness
A method of measuring the hardness of materials (resistance to penetration). Rockwell measures the hardness by pressing an indentor into the surface of the steel with a specific load, then measuring how far the indentor was able to penetrate. There are a number of Rockwell tests the most common is Rockwell B.

Rolling
A term applied to the operation of shaping and reducing metal in thickness by pressing it between rolls which compress, shape and lengthen it following the roll pattern. Steel is either hot rolled or cold rolled depending upon the product being manufactured,

Scale
A complex iron oxide formed on the steel surface during the hot rolling operation or formed on steel parts which are heat treated in the presence of oxygen.

Steel
A solid solution of iron and carbon. An iron-base alloy, malleable in same temperature range as initially cast, and containing carbon in amounts greater than .05% and less than about 2.00%. Other alloying elements may be present in significant quantities, but all steels contain at least small amounts of manganese and silicon.

Strain
Deformation produced on a body by an outside force.

Stress Relieving
A process of reducing residual stresses in material by heating to a suitable temperature and holding for a sufficient time. this treatment may be applied to relieve stresses inducted by casting, quenching, normalizing, machining, cold working or welding.

Temper
The state of or condition of a metal as to its hardness or toughness produced by either thermal or heat treatment and quench or cold working or a combination of same in order to bring the metal to its specified consistency. A condition produced in a metal or alloy by mechanical or thermal treatment and having characteristic structure and mechanical properties.

Tensile Strength
The maximum load in pounds per square inch that the sample will carry before breaking under a slowly applied gradually increasing load during a tensile test. The ratio of maximum load to the original cross-sectional area.

Toughness
The ability of a metal to absorb energy and deform plastically before fracturing. It is usually measured by the energy absorbed in a notch impact test such as the Charpy or Izod Impact Test. The area under the stress-strain curve in tensile testing is also a measure of toughness.

Ultimate Strength
See tensile strength.

Work hardening
An increase in resistance to deformation (hardness and strength) caused by cold working.

Yield Point
The yield point is the load per unit area at which a marked increase in deformation of the specimen occurs without increase of load during a tensile test.

Yield Strength
The point at which a material exhibits a strain increase without increase in stress. This is the load at which a material has exceeded its elastic limit and becomes permanently deformed. Stress corresponding to some fixed permanent

deformation such as .1 or.2% offset from the modulus or elastic slope.

Young's Modulus
Same as modulus of elasticity.

Section 4 - The Steels of interest to us.

OK - hopefully we now have a good comprehensive understanding of what the different properties of materials are - from elastic range and yield strength to ductility and ultimate strength.

Now what we need to do is develop and understanding of how and why some materials have these differing properties, followed by looking at the actual and relative properties of different irons and steels we will encounter, and finally which we should choose (or demand our suppliers and manufacturers choose) and why.

There are really three groups of metals that are of greatest interest and use to us, the builders and wheelers of hardcore 4x4s. They are all ferrous metals, meaning they are iron based and are magnetic. The groups are:

- cast irons
- carbon steels
- alloy steels

We will now examine each in a bit of detail.

Cast Irons

Ahhh - yes, the much maligned, hugely misunderstood cast iron. Let me get this off my chest right now. The term CAST IRON does not refer to a specific material with properties that we can discuss. It is a GENERIC TERM for a whole group of ferrous metals that are made up of iron, silicon, and carbon. The name has 2 parts - CAST referring to the fact that these metals can be readily poured into moulds (cast) when molten, to make parts, and IRON for the chief element that makes them up. It is sometimes (though rarely) necessary, and therefore just barely acceptable, to use the term "cast iron" when referring to the material from which something is made - but ONLY if we do not know the more specific type of cast iron. It is NEVER acceptable (though vast numbers of derelicts and miscreants are guilty of it!) to shorten this further and refer to any material by calling it 'cast' and using the word cast as a noun. In our world, "cast" is a verb, and is the method of making a part by pouring molten metal into a mould.

There, I feel better, don't you?

Now, there are several different types of cast irons that we should know about, and within each type there are often several different "grades." The different types of cast iron are distinguished by the form which the carbon takes - be it carbides, graphite, flakes, nodules, etc. The different types are:

Gray Iron
Composed of iron and silicon and carbon, with it's carbon content in the form of very thin interconnected flakes of graphite Gray iron possesses excellent castability and machinability so that complex parts can be readily cast and economically finish machined. The material has modest tensile strength values, good wear resistance, and good resistance to galling. It is economical to produce, cast and finish. Some examples of its use include: machine tool bases, ways and housings, disc brake rotors, cylinder blocks and heads.

White Iron
Having it's carbon content in the form of granules of iron carbide (due to low silicon content and rapid cooling when cast); white iron is very hard and brittle and virtually unmachinable. It is therefore of little practical use to us, despite having high compressive strength and good resistance to wear and abrasion. It is, however, often the starting point for malleable iron.

Malleable Iron
Malleable Iron has most of its carbon content in the form of irregularly shaped lumps or nodules of graphite mixed in the matrix (lattice) of iron. These nodules of graphite are not connected to one another though. Malleable iron is created by careful and precise heat treatment of solid white iron castings. The result is a cast iron that is extremely tough (toughest of all cast irons) and that can have (depending on the exact heat treatment) tensile strength and/or ductility similar to a mild carbon steel. It is not as easy to cast or machine as gray iron and therefore is usually only used to cast relatively simple parts. It is, however, often used for: hand tools (e.g. C-clamp, pipe wrench), brackets, hangars, axle housings, drive yokes, connecting rods, brake callipers, etc.

Nodular (Ductile) Iron
Named "Nodular Iron" because all of it's carbon content appears as tiny spherical nodules of graphite, and with carbon content of up to 10%, nodular iron combines the best properties of gray iron and malleable irons. It has both excellent castability as well as very good machinability while being the most ductile of all cast irons and having very high tensile strength (for a castable metal). With carefully controlled changes in chemical composition (it can be alloyed with other elements such as nickel, molybdenum, vanadium, etc - much the same as steel) and/or heat treatment it can be used to manufacture very strong, stiff, tough components. *The trucking and transportation industries have been quick to appreciate nodular castings as lighter and stronger replacements for complex steel weldments and for their ability to produce complex structural shapes - both cored and solid - that are strong, light, and cheap. Examples include such critical components as crankshafts, gears (including ring and pinion sets), and front suspension steering knuckles*. [4]

One of the most popular examples of nodular iron applicable to us must be the famous Ford 9 inch rear axle with the highly sought after nodular housing. Note also that some popular Dana axles (center sections) are cast from malleable iron (e.g. Dana 30) and some from Nodular Iron (e.g. Dana 44, 60)

Carbon Steels

It stands to reason that we cannot possibly describe or compare something unless we have a common language and a way to ensure we're talking about the same thing. In other words, a way to make sure we are comparing 'apples to apples". This is, in fact, one of the areas most full of error that I encounter on the web - people are not comparing "apples to apples".

Hopefully, after reading this section, we will all be able to do so more accurately.

Steel Designations.

Numbering systems currently in use today for steel have been developed over the years by various groups, including: trade associations, engineering societies, standards organizations, and private industry groups. Some examples are those developed by the American iron and Steel Institute (AISI), Society of Automotive Engineers (SAE), American Society for Testing and Materials (ASTM), American National Standards Institute (ANSI), Steel Founders Society of America, American Society of Mechanical Engineers (ASME), and the American Welding Society (AWS). You can see how it would be easy to fall into the trap of comparing apples to oranges! Not to worry, for our use, it's pretty easy as we generally stick to SAE/AISI designators. If you have or come across a steel with a different designator, there are many good trade publications that contain tables showing equivalent designations.

All carbon steels, the types we are interested in, (at least in North America) are designated using a standard four digit numbering system developed in cooperation between the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). For example, we are often used to seeing different steels referred to as 1020 or 4130 or 4340. The numbers are not arbitrary, they have specific meaning, and can tell us a lot about the steel in question. The first 2 digits of the designation are the "classification" of the steel. Carbon steels all belong to one of four (4) classifications, only two of which are any use to us - the 10xx and the 15xx. The four classifications of carbon steel are:

10xx—nonresulfurized carbon steel. Basic structural "low-carbon" or "mild" steel.
11xx—resulfurized carbon steel. Free machining steels, inherently brittle.
12xx—resulfurized and rephosphorized carbon steel.
15xx—nonresulfurized, high-manganese carbon steel. Basic carbon steel used for low-cost forgings.

The last two digits of the standard four digit designator indicate the approximate carbon content of the steel in tenths of a percent. For example, SAE 1020 contains approximately 0.20% carbon (actually from 0.17% to 0.23%).

Recall that the higher the carbon content the higher the ultimate tensile strength—and the lower the ductility.

Sometimes a suffix H is attached to a AISI/SAE number to indicate that the steel has been produced to prescribed hardenability limits. For example 1541H is a commonly used carbon steel in the manufacture of axle shafts.

There are a great many different specific types of carbon steel. The following information, taken from Carroll Smith's "Engineer to Win" and from the 24th Edition of the Machinery's Handbook (not the most modern, but the one I happen to own!) covers all or most of the types that are likely ever to be used by us to make parts from or used by manufacturers we might buy from.

SAE 1010-1015
This is the most common of the low carbon or mild steels. It is generally available as hot-rolled or cold-rolled sheet and it is used to form ERW tube in wall thicknesses below 0.065". Both formability and weldability are excellent. Like all of the low-carbon steels, 1010-1015 does not respond to heat treatment. Its strength levels are moderate and it was never intended to be used as a primary structure—lawn furniture, trailer frames and tooling only!

SAE 1018-1020
This is a very popular grade of low-carbon structural steel. It is available as hot-rolled or cold-finished bar, as ERW tube in wall thicknesses of 0.063" and up, as cold-drawn-seamless and DOM tube. It welds and forms very well and, while it does not respond to heat treatment, it can be case hardened by carburizing. I use it for just about everything other than suspension links— usually as DOM round tube or as cold-rolled sheet.

SAE 1025
This is the best of the low carbon steels. To the best of my knowledge it is now available only as seamless round tube—and that rarely. Before 4130 was developed, 1025 was the standard aircraft structural tubing. We don't use it simply because it is difficult to find and, if a tube fabrication deserves something better than 1020, it deserves to be made from 4130 and heat treated.[5]

And here's what the 24th edition of the Machinery's Handbook has to say on the matter:

Carbon Steels,-- SAE steels 1006, 1008, 1010, 1015: These steels are the lowest carbon steels of the plain carbon type, and are selected where cold formability is the primary requisite of the user. They are produced both as rimmed and killed steels. Rimmed steel is used for sheet, strip, rod, and wire where excellent surface finish or good drawing qualities are required, such a body and fender stock, hoods, lamps, oil pans, and other deep drawn and formed products. This steel is also used for cold heading wire for tacks, and rivets and low carbon wire products. Killed steel (usually aluminium killed or special killed) is used for difficult stampings, or where non-aging properties are needed. Killed steels (usually silicon killed) should be used in preference to rimmed steel for forging or heat treating applications.

These steels have relatively low tensile values and should not be selected where much strength is desired. Within the carbon range of the group, strength and hardness will rise with increases in carbon and/or with cold work, but such increases in strength are at the sacrifice of ductility or the ability to withstand cold deformation. Where cold rolled strip is used the proper temper designation should be specified to obtain the desired properties.

With less than 0.15 carbon, the steels are susceptible to serious grain growth, causing brittleness, which may occur as the result of a combination of critical strain (from cold work) followed by heating to certain elevated temperatures. If cold worked parts formed from these steels are to be later heated to temperatures in excess of 1100 degrees F., the user should exercise care to avoid or reduce cold working. When this condition develops it can be overcome by heating the parts to a temperature will in excess of the upper critical point, or at least 1750 degrees F.

Steels in this group, being nearly pure iron or ferritic in structure, do not machine freely and should be avoided for cut screws and operations requiring broaching or smooth finish on turning. The machinability of bar, rod and wire products is improved by cold drawing. Steels in this group are readily welded.

SAE 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1024, 1025, 1026, 1027, 1030: Steels in this group, due to the carbon range covered, have increased strength and hardness, and reduced cold formability compared to the lowest carbon group. For heat treating purposes they are known as carburizing or case hardening grades. When uniform response to heat *treatment is required, or for forgings, killed steel is preferred; for other uses, semi-killed or rimmed steel may be indicated, depending on the combination of properties desired. Rimmed steels can ordinarily be supplied up to 0.25 carbon.*

Selection of one of these steels for carburizing applications depends on the nature of the part, the properties desired, and the processing practice preferred. Increases in carbon give greater core hardness with a given quench, or permit the use of thicker sections. Increases in manganese improve the hardenability of both the core and case; in carbon steels this is the only change in composition that will increase case hardenability. The higher manganese variants also machine much better. For carburizing applications SAE 1016, 1018, and 1019 are widely use for thin sections or water quenched parts. SAE 1022 and 1024 are used for heavier sections or where oil quenching is desired, and SAE 1024 is sometimes used for such parts as transmission and rear axle gears. SAE 1027 is used for parts given a light case to obtain satisfactory core properties without drastic quenching. SAE 1025 and 1030, while not usually regarded as carburizing types, are sometimes used in this manner for larger sections or where greater core hardness is needed.

For cold formed or headed parts the lowest manganese grades (SAE 1017, 1020, and 1025) offer the best formability at their carbon level. SAE 1020 is used for fan blades and some frame members, and SAE 1020 and 1025 are widely used for low strength bolts. The next higher manganese types (SAE 1018, 1021 and 1026) provide increased strength.

All of these steels may be readily welded or brazed by the common commercial methods. SAE 1020 is frequently used for welded tubing. These steels are used for numerous forged parts, the lower carbon grades where high strength is not essential. Forgings from the lower carbon steels usually machine better in the as forged condition without annealing, or after normalizing. [6]

Some sample uses of 10xx and 15xx steels, taken from the Machinery's Handbook:

Steel	Use
1020	Camshafts, Fan Blades, Welded Tubing, Wrist Pins
1030	Brake Levers, Gear Shift Levers, Key Stock, Seamless Tubing
1035	Bolts and Screws
1040	Axles, Brake Levers, Camshafts, Connecting Rods, Carbon Steel Forgings, Studs
1045	Axle Shafts, Crankshafts, Carbon Steel Forgings, Ring Gears, Spline Shafts
1060	Clutch Disks, Clutch Springs, Lock Washers, Snap Rings, Valve Springs, Thrust Washers
1070	Clutch Disks, Plow Beams
1080	Agricultural Steel, Plow Discs, Plow Shares
1085	Clutch Disks, Leaf Springs, Mower Knives, Bumper bars
1095	Harrow Discs, Harrow Rake Teeth, Coil Springs

Adapted from: "Machinery's Handbook" 24th Edition. Erik Oberg, Franklin D. Jones, Holbrook L. Horton, Henry H. Ryffel, Robert E. Green; Industrial Press Inc., 1992 p.382-4

Alloy Steels

Alloy steels are steels that have had finite and precise amounts of alloying elements added to them during their manufacture. Alloying Elements are chemical elements added for improving the properties of the finished materials. Some alloying elements are: nickel, chromium, manganese, molybdenum, vanadium, silicon, copper. Small, precise changes in the exact chemistry of the steel can change the mechanical properties quite drastically. Generally, alloying elements are added to steel to maximize some particular mechanical property(ies). Of course, nothing in life is free, and there is always a price to pay. The more alloyed a steel is, the narrower it's appropriate use, as it becomes more and more specialized (narrow in focus) There is also a trade off in the reduction of other properties: as hardness and strength go up due to alloying with chromium and molybdenum - ease of welding and ductility go down, and of course cost goes up - in some cases WAY up.

Steel is considered to be alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more defined limits.

Common alloying elements and their effects are:

Element	Effect
Aluminium	Deoxidizes and restricts grain growth
Boron	Increases hardenability
Carbon	Increases hardenability and strength
Chromium	Increases corrosion resistance, hardenability and wear resistance
Lead	Increases machinability
Manganese	Increases hardenability and counteracts brittleness from sulphur
Molybdenum	Deepens hardening, raises creep strength and hot-hardness, enhances corrosion resistance and increases wear resistance
Nickel	Increases strength and toughness
Phosphorus	Increases strength, machinability, and corrosion resistance
Silicon	Deoxidizes, helps electrical and magnetic properties, improves hardness and oxidation resistance
Titanium	Forms carbides, reduces hardness in stainless steels
Tungsten	Increases wear resistance and raises hot strength and hot-hardness
Vanadium	Increases hardenability

Alloy steels are also designated using a standard four digit numbering system, very similar to that used for the carbon steels. However, the first two digits indicate the major alloying element or elements, whereas the last two digits again indicate the approximate carbon content of the steel in tenths of a percent. For example, SAE 4340 contains approximately 0.40% carbon.

The first two digits of an alloy steel's designation indicate the alloying elements and their percentages as follows:

13xx - Manganese-1.75 %
40xx - Molybdenum-0.20% or 0.25%
41xx - Chromium-0.50%, 0.80% OR 0.95% PLUS Molybdenum 0.25%
43xx - Nickel-1.83% PLUS Chromium 0.50% or 0.80% PLUS Molybdenum 0.25%
44xx - Molybdenum-0.53 %
46xx - Nickel-0.85% or 1.83% PLUS Molybdenum 0.20% or 0.25%
61xx - Chromium-0.60% or 0.95% PLUS Vanadium 0.13% or 0.15%
86xx - Nickel-0.55 % PLUS Chromium 0.50% PLUS Molybdenum 0.20%
87xx - Nickel-0.55% PLUS Chromium 0.50% PLUS Molybdenum 0.25%
88xx - Nickel-0.55% PLUS Chromium 0.50% PLUS Molybdenum 0.35%
92xx - Silicon-2.00%

Note that the hugely popular designation "Chrom-moly" steel has nothing to do with the shiny stuff on bumpers and hubcaps, but is in fact a reference to the fact that the steel in question has major alloying elements of Chromium and Molybdenum. That's why I prefer to write the abbreviation as Chrom-Moly, without the "e" on chrome. It is also popularly abbreviated as Cr-Mo, Cro-Mo, etc. Note that 41xx and 43xx alloy steels can and frequently ARE both refereed to as "Chrom-Moly Steel", though obviously the 43xx also has significant Nickel added.

Some characteristically enlightening, if rather opinionated, insight from my hero on the most common/popular alloy steels follows:

SAE 4130
Best known of the family of CHROME-MOLY steels, 4130 is often considered, in racing circles, to be the ideal steel for all high-strength/high-stress applications. IT IS NOT! In thin sections (that is, in tube or sheet form) its unique combination of excellent tensile strength, toughness and response to mild heat treatment combined with its good formability in the annealed condition and its outstanding welding characteristics make it virtually unbeatable for fabrications subject to high stress levels. It is critical that all welds be stress relieved. I prefer the use of OXWELD 32 CMS welding rod with 4130 for the simple reason that it both normalizes and heat treats well in conjunction with 4130. Many welders prefer to use a stainless rod, but the high nickel content of stainless welding rods means that the weldment will not respond well to heat treatment. Since I believe that not heat treating 4130 fabrications is DUMB (if you don't heat treat you end up with an expensive part with the same strength as 1020—and brittle weld areas). Smith's law says to use the heat-treatable rod for EVERYTHING. I heat treat 4130 fabrications to Rock-well C Scale 26 to 30 and no higher. This results in an ultimate tensile strength of about 130,000 psi with sufficient ductility that I do not have to worry about brittle parts. The other side of the 4130 coin, often unknown to (or at least unappreciated by) the racer, is that it possesses poor deep-heat-treating characteristics and has an inborn dislike of varying cross-sections. These characteristics make 4130 a poor choice for machined or forged parts—it doesn't forge very well anyway. It also doesn't machine very well, at least in the normalized condition—too gummy. Those people who make hubs, steering knuckles and the like from 4130 are kidding themselves—and their customers. It doesn't make very good shafts, either, as in drive shaft, or axle, or torsion bar.

SAE 4140
This is a deep hardening chrome-moly steel with excellent impact resistance, fatigue strength and general all-around toughness. It is commonly used for small-aircraft forgings. I use it in bar form for all of the little gub-bins and small parts that we are always machining. It doesn't weld as well as 4130 but it does weld satisfactorily. Welded to 4130 tube or sheet, with Oxweld 32 rod, a 4140 machined component can be heat treated to the same spec as 4130.

SAE 4340
This is the nickel-chrome-moly deep-hardening steel that we SHOULD use, in its vacuum-melted configuration, for our hub forgings, drive shafts, axles and the like. Its tensile strength, toughness, fatigue resistance, excellent deep-heat-treating characteristics and very high tolerance of stress reversals (which is just another way of saying that it has excellent fatigue resistance) make it just about unbeatable. It is also weldable (with care and a lot of pre-and post-heat) and eminently forgeable. In use it should be heat treated to the 180,000—200,000 psi range, maximum—although it can be taken to 220,000 psi without significant loss of toughness. The hardness range between Rockwell C Scale 46 and 48 should be avoided with this steel as it becomes brittle in this range.

SAE 4340 MODIFIED (300M)
This is, as you would expect, very similar to 4340... The addition of a trace of vanadium and an increase in the silicon level (while they have no notable effect on the hardness, strengths, or ductility of the resultant alloy) work miracles in the toughness and resistance to fatigue, producing a steel which, in the 270,000 to 300,000 psi range, is the toughest, most impact resistant and most fatigue resistant of the usually available steels. Unfortunately, even in the normalized condition, it is a bear to machine. Reducing the hardness by reducing the level of heat treatment or by tempering has the curious effect of reducing the tensile strength WITHOUT increasing the ductility or toughness. The most common use of this outstanding steel, also known as 300M, is for military and commercial aircraft landing gear. We use it for hubs, for drive shafts, axles and torsion bars—when we can afford it (or when we cannot afford NOT to use it). At its normal, heat-treated hardness level of Rockwell C 52/56 it is hard enough that we can and do run roller bearings directly on its surface. While the material is great, the heat treating is tricky. There is a very real danger of surface decarburization which can only be avoided by copper plating prior to heat treat. The ONLY heat treat specification for 300M is MIL H 6875, but there are tricks to every trade. MIL H 6875 calls out a two-hour quench at 575 degrees F. Doubling the quench time to four hours will notably increase the ductility and fatigue resistance of the finished product. Another trick is to absolutely forbid the heat treat shop to perform Rockwell or Brinell hardness tests on the actual part, supply a "test coupon" of the same material and cross-section wired to each part and insist that the coupon be heat treated along with the part and that all hardness tests be done on the test coupon. This is a good idea with ALL parts heat treated much above Rockwell C 40.

THE HIGH SILICON, NICKEL CHROME STEELS
These are usually known by trade names such as Hi-Tuff and Stress Proof. They contain up to about 3 % silicon and are, as the names suggest, tough as hell. They are popular for stock car and off-road racing axles—and the alloys are very suitable for these applications. They are not as good as 4340 M or even 4340, but they are also a damned sight cheaper and, especially where the minimum weights imposed are high, the fact that a part with the same strength and fatigue resistance can be made lighter by using a better steel may be a lot less significant than the cost difference. However, these steels are tough only because of the high silicon content, which is mainly in the form of longitudinal fibers or strings of silicon. This limits the efficient (and safe) use of the alloys to parts with minimal section changes and virtually no transverse machining (we don't

want to cut the longitudinal strings that make the stuff tough to start with, do we?). They also don't like being bent very much because that may rupture the silicon strings. Mind you, I have made a lot of street car antiroll bars from Stress Proof with excellent results and pretty severe bends—but in this case the bends are almost, by definition, in lightly stressed areas.[7]

Mechanical Properties

The following tables illustrate mechanical properties of various different types of steels of varying types - from hot rolled 1020 to cold finished 4340 chrom-moly alloy steel. They are taken from a variety of sources[8]. In addition to the actual specific numbers / data they contain, I believe they clearly illustrate some key concepts:

			Ultimate Strength				**Modulus Of Elasticity**				
Material	**Type**	Condition / Treatment	Tension (psi), T	Compression % of T	Shear % of T	Yield Point (psi)	In Tension E (millions of psi)	In Shear, % of E	% Elongation	Reduction of Area %)	Impact Strength (Izod) ft-lb
Gray Iron	**Class 20**	Class 20	20,000	360-440 %	160%		11.6	40%			
	Class 40	Class 40	40,000	310-340%	140%		17	40%			
	Class 60	Class 60	60,000	280%	100%		19.9	40%			
Malleable Iron			40-100,000			30-80,000	25	43%			
Nodular (ductile) Iron			60-120,000			40-90,000	23				
Cast Steel	**Carbon**		60-100,000	100%	75%	30-70,000	30	38%			
	Low Alloy		70-200,000	100%	75%	45-170,000	30	38%			
Magnesium			37-55,000		19-27,000	26-44,000	6.5				
Carbon Filament			280,000				110				
Aluminium	**6061-T6**		48,000		34,000	40,000	10.5				
	2024-T3		65,000		34,000	59,000	10.5				
	7075-T6		83,000		48,000	73,000	10.5				
Titanium			50-135,000			40-120,000	15-16.5				
Steel	**ASTM A-53**	Grade A	48,000	100%	75%	30,000	30	38%			
		Grade B	60,000	100%	75%	35,000	30	38%			
	1020	Cold Drawn Bar	82,000	100%	75%	70,000	30	38%	20%	65%	
	1020	Hot Rolled Bar	69,000	100%	75%	40,000	30	38%	38%	52%	
	1020	Normalized (1600*F)	64,000	100%	75%	50,250	30	38%	36%	68%	86.8
	1020	Annealed (1600*F)	57,000	100%	75%	42,750	30	38%	37%	66%	91
	1030	Quenched & Tempered (400*F)	123,000	100%	75%	94,000	30	38%	17%	47%	
	1030	Quenched & Tempered (800*F)	106,000	100%	75%	84,000	30	38%	23%	60%	

	1030	Quenched & Tempered (1200*F)	85,000	100%	75%	64,000	30	38%	32%	70%	
	1025 (low carbon		60-103,000	100%	75%	40-90,000	30	38%			
	1045 (mediu carbon		80-182,000	100%	75%	50-162,000	30	38%			
	1095 (high carbon		90-213,000	100%	75%	20-150,000	30	38%			
	1095 (high carbon	As-Rolled	140,000	100%	75%	83,000	30	38%	9%	18%	3
	1095 (high carbon	Normalized (1650*F)	147,000	100%	75%	72,500	30	38%	10%	14%	4
	1095 (high carbon	Annealed (1450*F)	95,250	100%	75%	55,000	30	38%	13%	21%	2
	1095	Quenched & Tempered (400*F)	216,000	100%	75%	152,000	30	38%	10%	31%	
	1095	Quenched & Tempered (800*F)	199,000	100%	75%	139,000	30	38%	13%	45%	
	1095	Quenched & Tempered (1200*F)	122,000	100%	75%	85,000	30	38%	20%	47%	
	4130	RC-30	136000 (81-179,000)	100%	75%	(46-161,000)	30	38%			
	4130	Normalized (1600*F)	97,000	100%	75%	63,250	30	38%	26%	60%	63.7
	4130	Annealed (1585*F)	81,250	100%	75%	52,250	30	38%	28%	56%	45.5
	4130	Hot Rolled & Annealed Bar	86,000	100%	75%	56,000	30	38%	29%	57%	
	4130	Hot worked & Annealed Tube	85,000	100%	75%	65,000	30	38%	20%		
	4130	Cold Drawn & Normalized	98,000	100%	75%	87,000	30	38%	21%	52%	
	4130	Cold Worked & Normalized	95,000	100%	75%	75,000	30	38%	15%		
	4130	Water quenched @ 1550*F Tempered at 1000	146,000	100%	75%	133,000	30	38%	17%	50%	
	4340	RC-44	208000 (109-220,000)	100%	75%	(68-200,000)	30	38%			
	4340	Normalized (1600*F)	185,500	100%	75%	125,000	30	38%	12%	36%	11.7
	4340	Annealed (1490*F)	108,000	100%	75%	68,500	30	38%	22%	50%	37.7
	4340	Hot Rolled & Annealed Bar	101,000	100%	75%	69,000	30	38%	21%	45%	

	4340	Cold Drawn & Normalized	111,000	100%	75%	74,000	30	38%	18%	42%	
	4340	Oil quenched @ 1550*F Tempered at 1000*F Bar	182,000	100%	75%	162,000	30	38%	15%	40%	
	4340	Quenched & Tempered (400*F)	272,000	100%	75%	243,000	30	38%	10%	38%	
	4340	Quenched & Tempered (800*F)	213,000	100%	75%	198,000	30	38%	10%	44%	
	4340	Quenched & Tempered (1200*F)	140,000	100%	75%	124,000	30	38%	19%	60%	
	300M (4340M	RC-52	270,000	100%	75%		30	38%			
	8630	Normalized (1600*F)	94,250	100%	75%	62,250	30	38%	24%	54%	69.8
	8630	Annealed (1550*F)	81,750	100%	75%	54,000	30	38%	29%	59%	70.2
	8630	Quenched & Tempered (400*F)	238,000	100%	75%	218,000	30	38%	9%	38%	
	8630	Quenched & Tempered (800*F)	185,000	100%	75%	170,000	30	38%	13%	47%	
	8630	Quenched & Tempered (1200*F)	112,000	100%	75%	100,000	30	38%	23%	63%	

- Note the various discrepancies - not all sources agree precisely on "the numbers". This is due to a variety of reasons - from differing test or calculation methods to the inerrant difficulty and imprecise repeatability of methods used to gather the data. The important point is - use the numbers for comparisons and as a guide. Actual design calculations should best me made using certified data from the specific supplier of the exact product to be used (i.e. the steel producer themselves) or a recognized standards organization such as the ASTM. Not only that - but this point clearly illustrates the folly of "designing to the limit" and demonstrates why engineers are trained to use "design factors" (used to be called safety factors in the past) of anywhere from 2 to 10 or more when making calculations.
- Note the general differences between the types of steel - from the mild, low carbon steels (e.g. 1020) to the high carbon, alloy steels (e.g. 4340 etc)
- Note also the (sometimes dramatically) different properties between different types (conditions) of the same steel - for example, between the hot rolled, normalized, annealed, and various tempered variants of the same steel.
- Note that, even without a stress/strain diagram we can tell something about a steel by looking at the difference between yield and ultimate tensile strengths. For example - the tensile strength of normalized 1020 is 64,000 psi or 27% greater than its 50,250 psi yield strength; whereas the tensile strength of normalized 4340 is 185,500 psi or 48% greater than its 125,500 psi yield strength!

Section 5 - Steel Production

How Steel is made into the useful products we need.

Recall that steel is produced from pig iron in a specialized furnace of a steel mill. This steel is produced in one of three special forms, known as slabs, blooms, or billets - each of which has an industry defined standard shape and size and which will be made into different useful products. Slabs eventually become steel plate, sheet metal or tubing. Blooms become something called "structural shapes" which we know as angle-iron, I-beams, etc. The last product is a billet, which is used to make solid steel bars and wire. Note that this is the correct use of the term "billet" - though we commonly misuse the term as either a noun meaning "any solid piece of metal from which we usually machine a part" or as an adjective meaning "a part machined from a single solid piece", as in "Look at my billet steering arms."

Whichever the particular shape that is started with or the finished product that is desired, the essential process is the same. The raw steel shape is turned into a useful steel product by one or more of various mechanical means - the raw steel is either pressed, rolled, formed, stamped, forged, or extruded into the final product. Each of these methods can be conducted at temperatures close to room temperatures (cold working) or at much higher temperatures, up to where the steel is nearly molten (hot working), or some combination thereof (for example, a particular steel product could be hot forged and then cold-finished. Carroll Smith explains the process further:

"*In the process, the physical characteristics of the metal are improved by breaking up the "as cast" crystal structure and "refinement" of the grain size...The yield strengths of almost all metals decrease notably with increasing temperature, so that a given amount of deformation can be achieved at much lower stress levels if the material is hot worked rather than cold worked. ..Almost all of the energy expended in the hot working of metals is dissipated as heat, leaving the metal's crystal* *structure largely unaffected and the metal ductile. On the other hand, while most of the energy expended in the cold working of a metal is also dissipated in the form of heat, some part of this energy remains within the crystal structure of the metal itself as "strain energy" in the form of various distortions of and dislocations in the crystal space lattice. Therefore, cold working, by decreasing the grain size and increasing the number of dislocations in the crystal lattice of the metal being worked, can increase the strength and hardness of the finished product—sometimes to a notable extent—at some cost in ductility...As you would expect, the different mill forming processes result in steel mill products of varying qualities and properties:*"

TUBE AND PIPE
Seamed tubing and pipe are roll formed from strips of sheet or plate and then welded. Seamless tubing (and pipe, which is merely tubing with thick walls intended primarily for the conveyance of liquids), on the other hand is pierced by a pointed mandrel while being fed by angled rollers and then either hot or cold finished.

STRUCTURAL SHAPES
Structural shapes—angles, zees, I-beams and the like— are hot rolled through progressive grooved rollers.

STEEL PLATE and SHEET
Steel sheet and strip are produced by progressively reducing a slab to the desired final thickness through hot-rolling mills. The better grades of steel sheet are hot rolled only to an approximation of final thickness and then cold rolled to final dimensions. Annealing and/or other thermal treatments before, during and after rolling are carefully controlled to produce a specified quality of finished sheet. Plate (sheet more than 1/4" thick) is produced in the same way.

BAR AND ROD STOCK-WIRE
Bar stock, rod, angles, I-beams and other shapes are also rolled to specified dimensions through progressive hot shaped rollers. Again, the higher grades are hot rolled only to approximate size and are cold drawn through hardened dies to their final dimensions. Hot-rolled round bar stock is also extruded, under unthinkable pressure, into wire. Special "tube rounds" are hot rolled and then used in the production of seamless pipe and tube. [9]

What's the difference to us, between hot and cold?

Depending on the exact product (tube, pipe, flat bar, plate steel, etc) the type of steel (mild, high carbon, alloy etc) and the manufacturer - MOST steel products we might use are available as either hot rolled, cold rolled, or hot rolled and cold finished. The difference is:

- Cold rolled or cold finished products are stronger - sometimes significantly so (up to 100% stronger (greater yield strength) - because of the improvement in the crystal lattice structure from improved grain size, shape, and orientation)
- Cold rolled or finished products are straighter, have a much smoother and uniform surface finish, and are made to much closer, more consistant dimensions
- Hot rolled products are more malleable and therefore easier to form
- Hot rolled products are supplied covered with scale, and are not as uniform in dimension as cold rolled

Steel Tubing

It is impossible to go into details about every type and shape and grade of steel product available or that we might be interested in. There are far too many, and availability will vary greatly depending on location and manufacturer/supplier.

That said, one of the most often used, most often asked about, and most often misunderstood products we use is the venerable round steel tubing.

Round steel tube is commonly available in a number of industry standard sizes. For an idea of the common industry sizes (inside diameter (ID), outside diameter (OD), and wall thickness) browse the supply catalogue of your local supplier or check the Pirate4x4.com tech database HERE and especially **HERE**.

Note that round steel mechanical tubing is NORMALLY ordered and supplied based on a specified OD and wall thickness. The ID is the result of these former 2 specs. There are however some exceptions to this - most notably in true seamless tubing.

Here are some Flash™ graphics of the different steel tube forming processes that I snagged from the excellent Steel Tube Institute of North America website.

Contnuous (butt welded) pipe process.
The continuous process produces a full range of pipe sizes from only a few different widths of skelp. The coils of skelp, or strip, are fed into the mill and their ends welded together to provide a continuous flow. The strip passes through a pre-heater and into a furnace. The heated strip is shaped into an arc of about 270° in a forming stand before passing into the welding stand. There a nozzle applies oxygen to the edges to further heat them as they are pressed and welded together. The pipe's OD and wall thickness are reduced in a stretch-reducing mill. Pipe is then cut to length, reduced to the required size in a sizing mill and water-cooled before being straightened. It is then ready for finishing

Typical Electric Resistance Welded tube process
Steel strip is unwound from coils and side-trimmed to control width and condition the edges for welding. The strip then passes through a series of contoured rolls which progressively cold-form it into a circular shape. The edges are forced together under pressure and welded by heating the steel to temperatures between 2200° F and 2600° F using copper contacts or coil induction. Weld flash is removed from the the inside and outside surfaces of the newly-formed pipe, and the weld zone is heat treated to ensure homogeneity between the base metal and weld. The weld is subjected to in-line nondestructive testing, and the tube then passes through a series of sizing rolls to attain its precise finished diameter. It is then straightened and cut to the desired finished length.

DOM tube being constructed, starting as ERW and then being drawn over a mandrel.
The manufacturing process for DOM tubing begins with coils of steel, which are slit to the proper width for the desired tube size. The strip is cold formed and passed through an electric resistance welder which joins the edges together, under pressure, to complete the tubular shape. After testing the weld's integrity, the tubing is cut to length for further processing

Seamless tube construction
The production process for seamless tube begins by heating a steel billet to about 2250° F. The red-hot billet is rotated and

drawn by rolls over a piercing rod, or mandrel. The action of the rolls causes the metal to flow over and about the mandrel to create a hollow tube shell. After reheating, the shell is moved forward over a support bar and is hot-rolled in several reducing/sizing stands to the desired wall thickness and diameter. The tube, which has grown significantly in length during the piercing and sizing processes, is then cut into sections and conveyed across a cooling bed to cool slowly in the air. It then receives whatever finishing processes are needed to meet customer requirements.

Steel tubing is usually supplied in one of the following forms:

Seamless Tube.
This is expensive and specialized stuff. It IS NOT the commonly used (and misreferenced) DOM tubing, as DOM tubing does indeed have a seam (albeit, almost invisible - more details below). True seamless tubing is uncommon in 4x4 and automotive use. It is seamless because it is manufactured by a process know as "extrusion" where a solid bar of steel is pierced down the center with a die, at unthinkable pressures, to form a tube. The process looks similar to how hollow pasta (macaroni etc) is made. There are 2 sub-types of seamless tube:

> **Cold Drawn Seamless (CDS) Tube** is normally drawn to O.D. and I.D. dimensions and produced to standard dimensional tolerances (this differs from most other types of tubing except DOM) . It is normally made from SAE 1018 and is considered good quality.
> **Hot Finished Seamless (HFS) Tube** is lower in cost than cold drawn and most applicable where precise dimensions and surface quality are of secondary importance. It is manufactured to O.D. and wall dimensions from SAE 1026 steel and is scaly, less dependable and not as strong as cold drawn tube.

Electric Resistance Welded (ERW) Tube
ERW is the most economical and readily available type of mechanical tuning. It is produced by taking a flat bar of steel and rolling it into a tube shape (picture rolling up a newspaper - but without any overlap) and then welding the seam - by, you guessed it - electric resistance - hence the name. Electric resistance welding is somewhat like a long, continuous spot weld. It's often computer controlled and extremely consistent. ERW is normally SAE 1010 (for wall thickness < 16 ga) or SAE 1020. ERW tube comes in 2 flavours:

> **Hot Rolled ERW (HREW)**
> HREW is rolled into a tube at elevated temperatures, usually way above room temperature. This produces a tubing that is more malleable and therefore easier to form but that is also not as strong, is supplied covered with scale, and not as uniform in dimension as cold rolled. It is also quite a bit cheaper than cold rolled.
>
> **Cold Rolled ERW (CREW)**
> CREW is manufactured by a process in which a steel bar is rolled into a tube and the seam welded, usually at room temperature. Compared to hot rolled, CREW is stronger - (greater yield strength) - because of the improvement in the crystal lattice structure from improved grain size, shape, and orientation imparted by being worked at cold (room) temperatures), straighter, has a much smoother and more uniform surface finish, and is made to much tighter, more consistent dimensions. It is the best economical choice for tube work, and because of the better surface finish and tighter dimensional tolerances it is much nicer to work with than HREW.

Drawn Over Mandrel (DOM)
Strong and well-finished DOM is an electric resistance welded tube tested for soundness of weld and drawn through a die and over a mandrel. This process imparts significantly improved mechanical properties to the tube, due to the cold working process. It is considered a high quality tube, and is normally constructed from SAE 1020 or 1026 steel. Note that, technically DOM refers to the process by which the tube is finished after having started as an ERW tube. Technically, DOM is not a type of steel tube, but rather a process. As so often happen though - in common use the term has become accepted to mean a specific type of tubing rather than a process. In this case, when people say "DOM" they normally mean an ERW tube drawn over a mandrel at (close to) room temperature and made from SAE 1020 steel. It is normally drawn to O.D. and I.D. dimensions. Here is what the Steel Tube Institute of North America has to say about DOM:

> ***The DOM Manufacturing Process***
>
> *The manufacturing process for DOM tubing begins with coils of steel, which are slit to the proper width for the desired tube size. The strip is cold formed and passed through an electric resistance welder which joins the edges together, under pressure, to complete the tubular shape. After testing the weld's integrity, the tubing is cut to length for further processing.*
>
> *The cold-drawing process creates a uniform, precision product with substantially improved tolerances, surface finish and tensile strength, increased hardness and good machinability. In this process, the tube is cleaned and annealed, and one end of each length is squeezed to a point so it can be gripped by the drawing mechanism. The tube is then drawn through one or more dies and over mandrels. This reduces the diameter of the tube and thins its walls to the required dimensions in a controlled fashion to provide the qualities desired in the finished product. Metallurgically, drawing improves the tube's concentricity, tensile strength, hardness and machinability. Close dimensional accuracy is achieved through tight control of both outside and inside diameters.*[10]

Alloy Steel Tubing
Is not really a different type of tubing, as it will be manufactured by one of the above described methods, usually by extrusion, but from alloy steel instead of mild steel. It is generally available in either the normalized or the annealed condition. Commonly referred to as chrom-moly tube - it has very strict welding process and post-welding heat treatment and stress relieving requirements. It is my opinion that it can (should) only be TIG or Oxy-Acetylene welded, and then only if proper stress relieving will be done post welding. Sure people MIG weld it all the time, and you can safely do so - BUT - what you have in the end is a superior tube with an inferior weld joint which reduces the overall strength of whatever you fabricated to the weakest link (the weld in this case) and so you have a very expensive structure that is no better overall than one made from 1020 DOM.

Exact chemical content, heat treatment, physical properties, production method and therefore mechanical properties will vary from one supplier to the next, even for seemingly similarly named products - the wise fabricator double-checks all assumptions carefully before building anything. Different suppliers will also have available different products. For example, Ryerson-Tull, one of North America's largest suppliers list in their catalogue of steel tubing between 1" and 2' OD, the following types (not all available in all sizes):

CDS, HFS, DOM, ERW, and a proprietary product they call "Ry-Star 512 Extra".

Many suppliers will have such special proprietary products - you will have to check with your supplier for its proprietary product properties and specs.

One thing that has to be watched out for is that the industry bends a lot of carbon steel tubing to make lots of things and so most carbon steel tubing is available in the annealed condition—woe to him who does not detect it before he builds the part. I have a very good friend who once got an entire roll cage cut, bent, fitted and tacked before he realized that his merry men were working with annealed boiler tube. The other thing that we don't want is "free machining tubing." I currently use round carbon steel DOM mechanical tubing for most things other than suspension links (there I use E4130N and stress relieve and heat treat after welding). For roll cages I use either 4130 or DOM 1020. I do not want to know about hot-finished tubing because I do not want to clean it. I am old enough to remember the days when English ERW tubing was liable to split along the weld seam. As a matter of principle (or, possibly, stubbornness) I do not use ERW or butt welded tube on the race car; although, since it is a lot cheaper, I use it all over the trailer and the shop.[11]

My personal mantra on the subject of steel tubing choice for 4x4s and rock crawler's is:

"You can't go wrong with 1020 DOM!"

Heat Treating

Heat treating and hardness - Two terns you hear A LOT, and so you should, for they are a critical part of the puzzle. In fact, when determining a materials suitability for any given task or part, heat treating itself is probably THE MOST SIGNIFICANT factor. It goes hand-in-hand with the type of material. In fact, very often, the more exotic and expensive alloys steels are "stronger" or "better" because they can be heat treated and hardened more thoroughly or deeper. In other words, chrom-moly steel is not just a product with wondrous properties - it's also a steel with certain alloying elements added to it that allows it to be hardened , and therefore made much stronger and more wear resistant, than other steels.

The trouble is - the topic of Heat Treating is HUGE, and quite complicated.....it involves physics, chemistry, math - all the fun Saturday night subjects :-) There is no possible way I can even scratch the surface in an article of this scope - but I can drop a little knowledge in the bucket of your collective minds, so that at least you will have a passing idea when you see or hear the terms, so that you may at least be able to ask intelligent questions, and so that you will have a place from which to start more detailed research if you need to.

Let's start with the definitions of the often seen, and often (erroneously) interchanged terms Hardness and Heat Treating.

Heat Treatment
An operation or combination of operations involving the heating and cooling of a metal in the solid state for the purpose of obtaining certain desirable conditions or change in properties or metallurgical structure. Heat treating operations include annealing, normalizing, quenching and tempering, etc.

Hardness
The ability of a metal to resist penetration, defined in terms of the measurement (Brinell, Rockwell,Scleroscope, Vickers, Knoop etc.) Normally, the hardness of steel varies in direct proportion to its strength – the harder it is, the stronger it is, and vice-versa.

Hardenability
This relates to the ability of steel to harden deeply upon quenching and takes into consideration the size of the part, the method of quenching and the analysis and grain size of the steel. Carbon steels are considered as shallow hardening and various alloy and tool steel grades are considered deep hardening or through hardening.

Hardening
Increasing the hardness by suitable heat treatment, usually involving heating and cooling. When applicable, the following more specific terms should be used: age hardening, case hardening, flame hardening, induction hardening, precipitation hardening, and quench hardening.

Now, recall from the beginning of the article that we said:

"You can see how there is a trade-off between a metal's malleability/ductility and its hardness/strength (which makes perfect logical sense – since malleability is the ease with which we can form it, by applying force, and strength is its ability to resist force). There are a whole group of people employed in a field called "physical metallurgy" whose job it is to figure out how to use things like alloying, heat treatment, and cold-working to skew this relationship (malleability/strength) in our favour, so that hopefully we can develop materials that are both strong and malleable."

Heat treating is the bread and butter of the physical metallurgist, it's probably the most important aspect of optimizing a steels properties for the job you want it to do, and it's effects can be enormous (for better or worse.)

So, we harden steel parts to make them "stronger", to make them better able to resist penetration and carry the loads imposed on them. We do so by heating them to very specific temperatures, holding them at those temperatures for very specific amounts of time (called "soaking") and then cooling them at very specific rates, sometimes quickly, sometimes in steps, and sometimes very slowly. Thus, the hardening of a steel is an operation achieved through heat treatment.

There are other reasons for heat treating as well, for example; to relieve stress. Stress relieving is process used to reduce internal residual stresses in a metal object by heating the object to a suitable temperature and holding for a proper time at that temperature. This treatment may be applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working, or welding.

So, I can't possible tell you how to heat treat steel here, but I can tell you a few important facts to keep in mind.

- Different methods of heat treating or hardening achieve different results. For example, an axle shaft that is "induction hardened" has a hard outer layer and a softer, more malleable inner core; compared to a shaft that is "through hardened" which will be hard all the way through. This in turn leads to the shafts having different properties.
- Different heat treating methods work more, or less, effectively with different steels and alloy steels. For example, you

cannot "through harden" 1541 steel axle shafts, and although you CAN induction harden 4340 cr-mo alloy steel, to do so without ALSO through hardening it would be a great waste, as the beauty (and strength) of 4340 lies in it's ability to accept a deep through hardening. In many cases there is a narrow range of acceptable matching alloys and heat treating methods - matching them to get the best properties possible in the part is an exact science.

- Heat treating is generally expensive, time consuming, and complicated. It produces much better parts, and you have to pay for it. The very best treatments are achieved through multiple steps - for example: an axle shaft that is through hardened and then induction hardened. Very few companies do this, and those that do produce a superior product - and will charge you for it.
- Heat treating, even if you know what you're doing can be difficult and temperamental. Done incorrectly or under poor control it can ruin expensive parts or produce inferior parts.

To illustrate the effect of hardening, look at this table, taken from "Engineer To Win". Note, for example, the difference between 4340 at Rockwell C 22 and 4340 at Rockwell C 44!

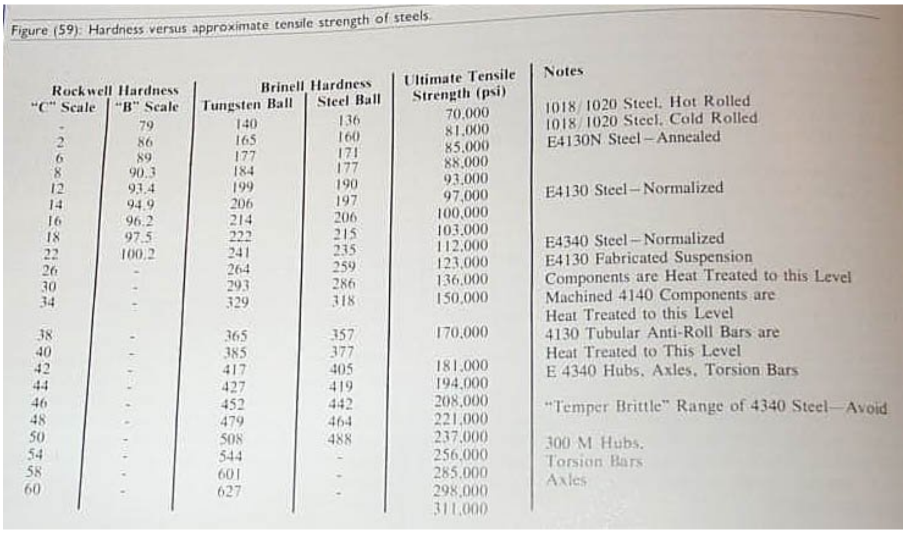


Figure (59): Hardness versus approximate tensile strength of steels.

Rockwell Hardness "C" Scale	Rockwell Hardness "B" Scale	Brinell Hardness Tungsten Ball	Brinell Hardness Steel Ball	Ultimate Tensile Strength (psi)	Notes
-	79	140	136	70,000	1018/1020 Steel, Hot Rolled
2	86	165	160	81,000	1018/1020 Steel, Cold Rolled
6	89	177	171	85,000	E4130N Steel – Annealed
8	90.3	184	177	88,000	
12	93.4	199	190	93,000	
14	94.9	206	197	97,000	E4130 Steel – Normalized
16	96.2	214	206	100,000	
18	97.5	222	215	103,000	
22	100.2	241	235	112,000	E4340 Steel – Normalized
26	-	264	259	123,000	E4130 Fabricated Suspension
30	-	293	286	136,000	Components are Heat Treated to this Level
34	-	329	318	150,000	Machined 4140 Components are Heat Treated to this Level
38	-	365	357	170,000	4130 Tubular Anti-Roll Bars are
40	-	385	377		Heat Treated to This Level
42	-	417	405	181,000	E 4340 Hubs, Axles, Torsion Bars
44	-	427	419	194,000	
46	-	452	442	208,000	"Temper Brittle" Range of 4340 Steel—Avoid
48	-	479	464	221,000	
50	-	508	488	237,000	300 M Hubs,
54	-	544	-	256,000	Torsion Bars
58	-	601	-	285,000	Axles
60	-	627	-	298,000	
				311,000	

I will leave the topic here by repeating the golden rule of heat treatment, and the providing a table of some more heat treatment terms:

"Heat treatment is the key to a steel parts strength and suitability - but it must be: matched carefully to the alloy, precisely selected for the desired results (properties achieved), and controlled carefully by an expert"

AIR HARDENING STEEL -An alloy steel which does not require quenching from a high temperature to harden but which is hardened by simply cooling in air from above its critical temperature range.

ANNEALING - Applies normally to softening by changing the microstructure and is a term used to describe the heating and cooling cycle of metals in the solid state. The term annealing usually implies relatively slow cooling in carbon and alloy steels. The more important purposes for which steel is annealed are as follows: To remove stresses; to induce softness; to alter ductility, toughness, or electric, magnetic or other physical and mechanical properties; to change the crystalline structure; and to produce a definite microstructure.

AUSTEMPERING - This is a method of hardening steel by quenching from the austenitizing temperature into a heat extracting medium (usually salt) which is maintained at some constant temperature level between 400” and 800” and holding the steel in this medium until austenite is transformed to bainite. The austempering process is limited to sections less than `/2” diameter. The advantages of this method of interrupted quenching are increased ductility and toughness at the resulting hardness of RC 45-55.

AUSTENITE - The solid solution of iron and carbon which is attained by heating to high temperatures above the upper critical temperature. This temperature or temperature range is called the austenitizing temperature and must be attained to obtain the proper microstructure and full hardness of steel in heat treating. The austenitizing temperature varies for the different grades of carbon, alloy and tool steels.

BAINITE - A decomposition or transformation product of austenite which is a type of microconstituent or structure in steel. This term is used by metallurgists to describe a particular structure of steel when the steel is polished, etched and examined with a microscope.

BRINELL HARDNESS - A hardness number determined by applying a 3000 kilogram load to the surface of the material to be tested through a hardened steel ball of 10mm. The diameter of the depression is measured and the hardness is the ratio of load to spherical area of the impression. Tables of numbers have been prepared, and the hardness is read from the table from the diameter of the depression.

CARBURIZING - Adding carbon to the surface of steel by heating the metal below its melting point in contact with carbonaceous solids, liquids, or gases.

CASE HARDENING - A heat treatment or a combination of heat treatments of surface hardening involving a change in the composition of the outer layer of an iron-base alloy in which the surface is made substantially harder by inward diffusion of a gas or liquid followed by appropriate thermal treatment. Typical hardening processes are carburizing, cyaniding, carbo-nitriding and nitriding.

CYANIDING - Surface hardening by carbon and nitrogen absorption of a steel article or a portion of it by heating at a suitable temperature in contact with cyanide salt, followed by quenching.

DECARBURIZATION - When steel is subjected to high temperatures, such as are used in hot rolling, forging, and heat treating in a media containing air, oxygen, or hydrogen there is a loss of carbon at the surface which is known as decarburization. This resultant loss of carbon or chemistry change at the surface of the steel part reduces the strength of the part by reducing the size of the section and produces a softer surface hardness than the core of the part.

FLAME HARDENING - A heat treat method used to harden the surface of some parts where only a small portion of the surface is hardened and where the part might distort in a regular carburizing or heat treating operation. The operation consists of heating the surface to be hardened by an acetylene torch to the proper quenching temperature followed immediately by a water quench and proper tempering. Generally wrought or cast steels with carbon contents of .30 to .40%, low alloy steels, and ductile and malleable cast irons are suitable for flame hardening.

HARDENABILITY- This relates to the ability of steel to harden deeply upon quenching, and takes into consideration the size of the part and the method of quenching. The test used to determine the hardenability of any grade of steel is the Jominy Test.

HARDENING - The heating and quenching of certain iron-base alloys from a temperature above the critical temperature range for the purpose of producing a hardness superior to that obtained when the alloy is not quenched. This term is usually restricted to the formation of martensite.

HARDNESS - The ability of a metal to resist penetration. The principle methods of determining hardness of steel are the Rockwell, Brinell and Scleroscope Tests.

HEAT TREATMENT - An operation or combination of operations involving the heating and cooling of a metal or an alloy in the solid state for the purpose of obtaining certain desirable conditions or properties.

MARTEMPERING OR MARQUENCHING - This is a method of hardening steel by quenching from the austenitizing temperature into some heat extracting medium, usually salt, which is maintained at some constant temperature level above the point at which martensite starts to form (usually about 450” F.), holding the steel in this medium until the temperature is uniform throughout, cooling in air for the formation of martensite and tempering by the conventional method. The advantages of this method of interrupted quenching are a minimum of distortion and residual strains. The size of the part can be considerably larger than for austempering. MARTENSITE - A microconstituent or structure in quenched steel which has the maximum hardness of ally of the other steel structures resulting from the transformation of austenite.

NITRIDING - See case hardening.

NORMALIZING - Heating steels to approximately 100 F above the critical temperature range followed by cooling to below that range in still air at ordinary temperatures. This heat treat operation is used to erase previous heat treating results in carbon steels to .40% carbon, low alloy steels, and to produce a uniform grain structure in forged and cold worked steel parts.

OIL HARDENING - A process of hardening a ferrous alloy of suitable composition (generally alloys) by heating within or above the transformation range and quenching in oil.

PEARLITE - Another microscopic structure of steel which is produced by slow cooling or air cooling low to medium carbon and low alloy steels from the austenitic state.

QUENCHING AND TEMPERING - In this operation the procedure consists of heating the material to the proper austenitizing temperature, holding at that temperature for a sufficient time to effect the desired change in crystalline structure, and quenching in a suitable medium - water, oil or air depending on the chemical composition. After quenching, the material is reheated to a predetermined temperature below the critical range and then cooled under suitable temperatures (tempering).

SCLEROSCOPE OR SHORE HARDNESS - A hardness test performed on a Shore Scleroscope Hardness Tester. The hardness is determined by the rebound of a diamond pointed hammer (or tip) when it strikes the surface of a specimen. The hammer is enclosed in a glass tube and the height of the rebound is read either against a graduated scale inscribed on the tube, or on a dial, depending on the model used. This type of hardness testing is generally used on large parts which cannot be tested by either using a Rockwell or Brinell machine.

SUB-CRITICAL ANNEALING - Also Stress Relief Annealing. A heat treating operation used to relieve or dissipate stresses in weldments, heavily machined parts, castings and forgings. The parts are heated to 1150” F., uniformly heated through, and are either air cooled from temperature or slow cooled from temperature depending on the type of part and subsequent finishing or heat treating operations.

TEMPERING - Also termed drawing. Reheating hardened, usually quenched, steel to some temperature below the lower critical temperature followed by any desired rate of cooling after the steel has been thoroughly soaked at temperature. Usual tempering temperatures are 300” to 1100” F.

WATER HARDENING - High carbon grades of tool steel, straight carbon steels and low alloy steels that are hardened by quenching in water during the heat treating operation.

Section 7 - Design principles

coming soon !!

This section will be added at a later date and will include discussion on the flow of stress, how removing material can increase strength, how shapes are strong, etc.

For now, dig this:

Modes of Failure

There are only 3 ways that steel parts can break. That is, there are only 3 ways that the atomic bonds of the steel's crystal lattice structure can be broke. They are: tension, compression, and shear. Tension is the action of pulling. Steel parts can be pulled apart - for example, if you grasped 2 ends of a steel bar and pulled lengthwise till is pulled apart like taffy - it would have failed in tension. Compression is the action of being pressed on. We don't generally see steel 4x4 parts failing in compression, but it can still affect us. A more obvious example of compression failure might be a concrete block that is loaded with weight until it crumbles into dust. Now ask yourself - how many rigs have I seen in driveways jacked up on stacks of concrete building blocks? Shear is the action of slicing or cutting through something. Take 2 pieces of steel plate and bolt them together through a hole drilled in each. Now, slide the 2 pieces away from each other in opposite directions and if the bolt fails by getting sliced in half, it has failed in shear.

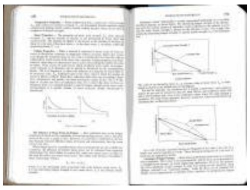
UTS or Ultimate Tensile Strengths for different materials or components are readily published, as they are comparatively easy to determine by testing. A sample is placed into a machine and pulled until it comes apart, the force required is recorded. Compressive strengths are not commonly published, but they are available. Shear strengths for steel products are generally regarded to lie in the range of 60-80% of the UTS of the material.

There may seem to be other modes by which a part can fail, but on examination these are really just some combination of the above 3 modes of failure. For example, bending is really just a part that is experiencing tension on one side and compression on the other. Torsional loading is really a combination of tension, compression, and shear all at once (and is therefore fairly complicated to calculate)

Section 8 - Fatigue

coming soon !!

This section will be added at a later date and will include discussion on fatigue properties of steel. For now, I will whet your appetite with these scans from the Machinery's Handbook (click on the thumbnail for larger version), no doubt breaking half a dozen international copyright laws. If you are a copyright holder whom I have infringed and you object, please contact me and I will remove the offending material.



Fatigue Properties

S-N diagrams

Influence of Mean Stress on Fatigue

Goodman's Diagram

Cumulative fatigue Damage

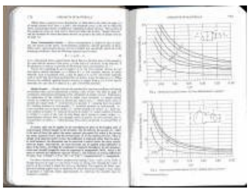
Modes of fatigue failure

- Low/High-Cycle Fatigue
- Thermal Fatigue
- Corrosion Fatigue
- Surface or contact fatigue
- Combined creep and fatigue

Factors of Safety (Design Factors)

Working Stress

Stress concentration Factors



Simple Stresses

Diagram - Stress-concentration factor for a fillited shaft in tension

Diagram - Stress-concentration factor for a fillited shaft in torsion

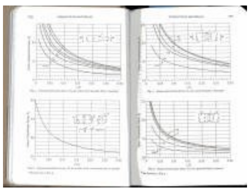


Diagram - Stress-concentration factor for a shaft with shoulder fillet in bending

Diagram - Stress-concentration factor for a shaft with a transverse hole, in torsion

Diagram - Stress-concentration factor for a grooved shaft in bending

Diagram - Stress-concentration factor for a grooved shaft in torsion

Diagram - Stress-concentration factor for a shaft with a transverse hole in bending

Deflections

Table of Simple Stresses (including shaft in torsion)

Section 9 - Dispelling myths / FAQ

Under development !!

This section will be a sort of practical summary of all the knowledge contained in this article. It will address several common myths and also serve as a FAQ. It will hopefully be periodically updated and amended as required. Ultimately I hope it contains not only the answers to the myths and frequently asked questions, but also the reasoning. In the interim, however, it may just contain blunt answers and the reader will have to return to the theory in the article and make the connections themselves.

Q: Which is stronger in torsion - a hollow or solid shaft of the same size (OD)?

A: Solid. However, depending how much material is removed from the middle of the hollow shaft (i.e. how thick the walls remain) often the hollow shaft saves significant weight while sacrificing VERY LITTLE strength. However, the solid shaft WILL ALWAYS ultimately be stronger, just sometimes not by very much.

The following offer proof:

Table giving Comparative Torsional Strengths and weights of Hollow and Solid Shafting with Same Outside Diameter.[12]

and

Eric Ruhl's proof, posted on the Pirate4x4.com Bulletin Board.

Q: What should I use for my cage/bumper/tube chasis/whatever - HREW, DOM, or Cr-Mo?

A: Depends on your budget, needs, and ability to weld and stress relieve. 1020 DOM is an excellent all-around choice for most - clean, tight tolerances, good strength, reasonable cost, and fairly readily bent and welded. HREW is a good low-cost, easy to work with alternative for non-critical applications or mild use. Cr-Mo is the top of the strength scale (depending on condition, of course) but with some serious drawbacks: Unless properly TIG of Oxy-Acetylene welded AND properly post-weld stress-relieved all you have is an expensive pile of tubing no stronger than 1020 DOM (all you Cr-Mo MIG welders take note!!). It is also expensive and a bear to bend, cut, drill, and machine.

Q: Is pipe only for plumbing?

A: Certainly not. In fact, the word "pipe" is often grossly misused. It is, of course, not a designation of any particular product or material, and therefore confers no meaning in terms of any particular mechanical properties (strength, ductility, impact resistance, etc.) Pipe is a type of steel tube, usually intended to convey liquid or gas. I say usually because, in the construction industry, material labelled "pipe" is frequently used in the construction of bridges, buildings, oil rigs etc. Pipe, like any steel tube comes in various grades and conditions - some quite suitable for building 4x4 parts, and some not at all - just like other steel products. You have to know what you're dealing with, what its condition is, and what its properties are before you can decide. Here is some comparative data on one common type of pipe, though again, it is in no way representative of all "pipe"

The ASTM A-53 spec is the American Society for Testing and Materials specification that covers seamless and welded steel pipe intended for mechanical and pressure applications, including ordinary uses in steam, water, gas, and air lines. Note that it says "mechanical applications" whcih means building things. Also note that the yield strength of this most common type of pipe is 30,000-35,000 compared to 32,000-40,000 psi for common 1010 ERW, CREW, and HREW compared to 70,000 psi for 1020 DOM and 90,000 psi for 4130 Cr-Mo DOM.

ASTM A-53 PIPE

TABLE 1 **Chemical Requirements**

	Carbon	Manganese	Phosphorus	Sulfur	Copper[A]	Nickel[A]	Chromium[A]	Molybdenum[A]	Vanadium[A]
	Composition, max, %								
Type S (seamless pipe)									
Open-hearth, electric furnace or basic oxygen:									
Grade A	0.25	0.95	0.05	0.045	0.40	0.40	0.40	0.15	0.08
Grade B	0.30	1.20	0.05	0.045	0.40	0.40	0.40	0.15	0.08
Type E (electric-resistance-welded)									
Open-hearth, electric furnace or basic oxygen:									
Grade A	0.25	0.95	0.05	0.045	0.40	0.40	0.40	0.15	0.08
Grade B	0.30	1.20	0.05	0.045	0.40	0.40	0.40	0.15	0.08
Type F (furnace-welded pipe)									
Open-hearth, electric furnace or basic oxygen:									
Grade A	0.30	1.20	0.05	0.045	0.40	0.40	0.40	0.15	0.08

[A] The combination of these five elements shall not exceed 1%.

TABLE 2 **Tensile Requirements**

	Type F	Types E and S	
	Open-Hearth, Basic Oxygen, or Electric-Furnace, Grade A	Grade A	Grade B
Tensile strength, min, psi (MPa)	48 000 (330)	48 000 (330)	60 000 (415)
Yield strength, min, psi, (MPa)	30 000 (205)	30 000 (205)	35 000 (240)
Elongation in 2 in.	A	A	A

[A] The minimum elongation is 2 in. (50.8 mm) shall be that determined by the following equation: $e = 625\ 000\ A^{0.2}/U^{0.9}$ where:

e = minimum elongation in 2 in. (50.8 mm) in percent rounded to the nearest 0.5%,
A = cross-sectional area of the tension test specimen in square inches, based on specified outside diameter or nominal specimen width and specified wall thickness rounded to the nearest 0.01 in.^{2} If the area thus calculated is greater than 0.75 in.^{2}, then the value 0.75 shall be used, and
U = specified tensile strength, psi.

Q: What's the difference in how tube and pipe are called-out (described) in terms of dimension (size)?

A: Round steel mechanical tubing ("tube") is called out by either a specified OD and wall thickness (with resulting ID) or in other cases by specifying both an OD and ID (and getting a resulting wall thickness). In practical terms these amount to the same thing and you usually order steel tubing by asking for an OD and wall thickness.

Pipe is slightly more complicated:

The document: "Wrought Steel Pipe - ANSIB36.10-1979" covers dimensions of welded and seamless wrought steel pipe, for high or low temperatures or pressures. The word "pipe" as distinguished from "tube" is used to apply to tubular products of dimensions commonly used for pipelines and piping systems. Pipe dimensions of sizes 12 inches and smaller have outside diameters numerically larger than the corresponding nominal sizes whereas outside diameters of tubes are identical to nominal sizes.

The size of all pipe is identified by the nominal pipe size. The manufacture of pipe in the nominal size of 1/8" to 12" inclusive, is based on a standardized outside diameter. This OD was originally selected so that pipe with a standard OD and having a wall thickness which was typical of the period would have an inside diameter approximately equal to the nominal size. Although there is now no such relation between the existing standard thicknesses, ODs and nominal sizes, these nominal sizes and standard ODs continue in use as "standard".

Industry publications will list pages of tables of these "standard" dimensions. For example. A 1" pipe will have an OD of 1.315" and a wall thickness depending on its schedule as follows.

Schedule 40 - 0.133
Schedule 80 - 0.179
Schedule 160 - .250

there is a table available online in the Pirate4x4.com tech section HERE

Section 10 - Equations:

The following equations are provided for the mathematically oriented reader simply for the purpose of understanding and illustrating the concepts discussed in this article: **DO NOT USE THEM for calculations**, as they may not include critical elements suchas design factor, impact loads, safety margins, and fatigue factors! (that's what professional Engineers are for :-)

Stress:

Stress (normal)

Stress is the ratio of applied load to the cross-sectional area of an element in tension and is expressed in pounds per square inch (psi) or kg/mm^2.

$$\text{Stress, } \sigma = \frac{Load}{Area} = \frac{L}{A}$$

Strain

Strain (normal)

A measure of the deformation of the material that is dimensionless.

$$\text{Strain, } \epsilon = \frac{\text{change in length}}{\text{original length}} = \frac{\Delta L}{L}$$

Modulus of Elasticity

Modulus of elasticity

Metal deformation is proportional to the imposed loads over a range of loads.

Since stress is proportional to load and strain is proportional to deformation, this implies that stress is proportional to strain. Hooke's Law is the statement of that proportionality.

$$\frac{Stress}{Strain} = \frac{\sigma}{\epsilon} = E$$

The constant, E, is the modulus of elasticity, Young's modulus or the tensile modulus and is the material's stiffness. Young's modulus is in terms of 10^6 psi or 10^3 kg/mm^2. If a material obeys Hooke's Law it is elastic. The modulus is insensitive to a material's temper. Normal force is directly dependent upon the elastic modulus.

Design (Safety) Factor

Safety factor is a function of design stress and yield strength. The following equation denotes safety factor, f_s.

$$f_s = \frac{YS}{DS}$$

Where YS is the Yield Strength and DS is the Design Stress

Roy McBride and Dave Towers of Heriot Watt University excellent tutorial on Torsion of shafts with circular symmetry an MS Word .doc file. Also available in .pdf format

Section 11 - Tables:

The following tables present a great deal of information that you may find interesting or of use:

Typical Mechanical Properties of round Carbon Steel Tube and Pipe - compares HREW, DOM, Pipe etc.

Typical Mechanical Properties of round Alloy Steel Tube - Chrom-moly tube properties

Typical Mechanical Properties of Seamless and ERW Pipe - it's not just for poop!

.Section 12 - Glossary:

General Steel and Iron Terms

Alloy
The mixture of any element with a pure metal. However, there are several elements regularly occurring in plain carbon steel as manufactured, such as carbon, manganese, silicon, phosphorous, sulphur, oxygen, nitrogen and hydrogen. Plain carbon steel is therefore an alloy of iron and carbon and these other elements are incidental to its manufacture. Steel does not become alloy steel until these elements are increased beyond their regular composition for a specific purpose, or until other metals are added in significant amounts for a specific purpose.

Alloying Elements
Chemical elements added for improving the properties of the finished materials. Some alloying elements are: nickel, chromium, manganese, molybdenum, vanadium, silicon, copper.

Alloy Steel
Steel is considered to be alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: Manganese 1.650/0, silicon,.60%, copper,.600/0, or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy. Steels: Aluminium, chromium up to 3.9~, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect.

Annealing
The process of putting material in its softest condition for further processing. This is normally done by heating material to a certain temperature, then cooling it under controlled conditions.

Billet
A solid semi-finished round or square product that has been hot worked by forging, rolling or extrusion. An iron or steel billet has a minimum width or thickness of 11~! inches and the cross-sectional area varies from 21/4 to 36 square inches.

Brinell Hardness
A measurement of a metals hardness (or the ability to resist penetration). A ball is pressed into a sample under a 3000 kilogram load. The diameter of the depression is measured, and the hardness is the ratio of the load to the spherical area of the impression.

Carbon Steel
Steel is classified as carbon steel when no minimum content is specified or required for aluminium, boron, chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium, or any other element added to obtain a desired alloy effect; when the specified minimum for copper does not exceed .40% or when the maximum content specified for manganese does not exceed 1.650/0; silicon .600/0; copper .60%.

Case-Hardening
A process of hardening a ferrous alloy so that the surface layer or case is made substantially harder than the interior or core. Typical case-hardening processes are carburizing and quenching, cyaniding, carbonitriding, induction hardening and flame hardening.

Charpy Test
A pendulum-type single-blow impact test in which the specimen, usually notched, is supported at both ends as a simple beam and broken by a falling pendulum of given weight. The energy absorbed, as determined by the subsequent rise of the pendulum, is a measure of impact strength or notch toughness and is a measurement in foot-pounds. The test specimen is 2” or 2.165” long, .394” square and has a key hole type notch in the center made by centering a No. 47 drill .160” from one side and sawing through the hole.

Cold Drawing
This is a process for finishing a hot rolled rod or bar at room temperature by pulling it through the hole of a die of the same shape but smaller in size. The bars or rods are cleaned of scale by pickling or other methods prior to cold drawing and then coated with lime which aids as a lubricant in the drawing operation.

Cold Finishing
The cold finishing of steel, generally used for bars and shafting, may be defined as the process of reducing their cross sectional area, without heating, by one of five methods: Cold rolling, Cold drawing and grinding, Turning and grinding, Cold drawing, or Turning and polishing.

Cold Forming
Forming a metal at or near room temperatures.

Cold Rolling (Cold Finishing)
A forming process in which metal is rolled or drawn through dies, usually at room temperature. This produces a product with certain advantages over hot rolled steel, such as tighter tolerances, increased properties, improved finish and straightness.

Cold Rolling
The cold working of hot rolled material by passing it between power driven rolls. The process is generally used for flat bars of such a size that they cannot be pulled through a die and for the production of cold rolled sheets by cold reducing hot

rolled and pickled sheets. Whereas wire and sheets are cold drawn and cold rolled continuously from coil, bars are individually cold drawn.

Cold Working
Plastic deformation of a metal at a temperature low enough to insure strain hardening.

Core
The center portion of a piece of steel which may be of different chemical composition than the outside, as in the case of carburized parts or which may have different mechanical properties than the outside due to the failure of penetration of heat treatment effect.

Decarburization
The loss of carbon from the surface of a ferrous alloy. Decarburization is a common surface condition of hot rolled steel and is produced during the heating and rolling operations when atmospheric oxygen reacts with the heated surface removing carbon.

Ductility
The ability of a material to be plastically deformed without fracturing

Elastic Limit
The greatest stress which a material is capable of developing without a permanent deformation remaining upon complete release of the stress.

Elongation
The amount of permanent extension in the vicinity of the fracture in the tensile or tension test; usually expressed as a percentage of the original gauge length, such as 25% in 2” or 21% in 8”.

Endurance Limit
Also known as fatigue limit, a limiting stress, below which metal will withstand without fracture an indefinitely large number of cycles of stress. If the term is used without qualification, the cycles of stress are usually such as to produce complete reversal of flexural stress. Above this limit failure occurs by the generation and growth of cracks until fracture results in the remaining section.

Fatigue
The phenomenon of the progressive fracture of a metal by means of a crack which spreads under repeated cycles of stress.

Fatigue Resistance
The ability of a metal to withstand repeated and varying loads.

Ferrous
Metals or alloys that contain appreciable amounts of iron.

Forging
A hot working operation generally involving plastic deformation of metal at high temperatures into desired shapes with compressive force.

Fracture Toughness
The ability of a material at a given temperature to resist further crack propagation, once a crack has started.

Free Machining (Improved machining)
A term to describe a type of steel that has been modified, usually by adding sulphur, lead, or selenium to increase its machinability.

Galvanizing
The process of applying a coating of zinc to cold-reduced sheet, bar, structural, or to fabricated parts made from steel. The coating is applied by hot dipping or electrolytic deposition and is applied to make product more corrosive resistant.

Hardness
The ability of a metal to resist penetration, defined in terms of the measurement (Brinell, Rockwell,Scleroscope, Vickers, Knoop etc.)

Hardenability
This relates to the ability of steel to harden deeply upon quenching and takes into consideration the size of the part, the method of quenching and the analysis and grain size of the steel. Carbon steels are considered as shallow hardening and various alloy and tool steel grades are considered deep hardening or through hardening.

Hardening
Increasing the hardness by suitable heat treatment, usually involving heating and cooling. When applicable, the following more specific terms should be used: age hardening, case hardening, flame hardening, induction hardening, precipitation hardening, and quench hardening.

Heat Treatment
An operation or combination of operations involving the heating and cooling of a metal in the solid state for the purpose of obtaining certain desirable conditions or change in properties or metallurgical structure. Heat treating operations include annealing, normalizing, quenching and tempering, etc.

Hot Rolled
Hot rolled products are those products that are rolled to finish at temperatures above the recrystallation temperature.

Impact Test
A test used to determine the impact energy measured in foot pounds, to fracture a material by means of an Izod or Charpy test.

Impact Toughness
The ability of a material to resist fracture under an impact.

Inclusions
Nonmetallic materials occurring in metals. More specifically in steel; oxides, sulphides, and silicates which are mechanically held during solidification of the ingot.

Ingot
A steel casting that is cast into a mould which when solidified will be rolled in a blooming mill to plates, slabs for sheets, or blooms and billets into structurals and bars.

Izod test
An impact test similar to the charpy with the difference being in the test specimen. In the Izod test the specimen is 2.953" long,.3937" square with a 45" notch located 1.1024" from the impact end. The distance from the bottom of the notch to the opposite side is .315".

Killed Steel
Steel deoxidized with a strong deoxidizing agent such as silicon or aluminium in order to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification of the molten steel in the ingot. Killed steel products will produce a more chemically uniform analysis from the bottom to the top of the ingot. Killed steel is considered having less chemical segregation than semi-killed or rimmed steel.

Machinability
The relative ease of machining a metal. Machinability index for various steels and machinability tables are available for comparing machining rates with 1212 steel as the standard for carbon and alloy steels and W-l as a standard for tool steels.

Mechanical Properties
The properties of a material that reveal its elastic and inelastic behaviour where force is applied, thereby indicating its suitability for mechanical applications; for example, modulus of elasticity, tensile strength, elongation, hardness and fatigue limit.

Modulus of Elasticity
Measure of stiffness. The ratio within the limit of elasticity of the stress to corresponding strain. The stress in pounds per square inch is divided by the elongation in fractions of an inch for each inch of the original gauge length of the specimen. The modulus of elasticity for cold rolled steel is 29,500,000 psi and for other steels varies between 28,600,000 and 30,300,000 psi.

Nitriding
Adding nitrogen to iron-base alloys by heating the metal in contact with ammonia gas, or other suitable nitrogenous material. Nitriding is conducted at a temperature usually in the range of 935-1000" F. and produces surface hardening of the metal without quenching.

Oxidation
The addition of oxygen to a compound. Exposure to atmosphere sometimes results in oxidation of the exposed surface, hence a staining or discolouration. Rust is oxidation. This effect is increased with temperature increase to the point where heavy scale is formed and the steel product has a decarburized surface.

Physical Properties
Those properties familiarly discussed in physics, exclusive of those described under mechanical properties; for example: density, electrical conductivity and coefficient of thermal expansion.

Pickle
Chemical or electrochemical removal of surface oxides (surface scale). Pickled steels must be oiled or they will rust rapidly.

Pickling
The process of removing hot rolled mill scale from billets, bars or hot rolled sheets with sulphuric or hydrochloric acid. The scale is removed for hot rolled pickled and oiled sheets or for further processing of the hot rolled steel product into cold drawn bars and wire and cold rolled sheets and strip.

Plastic Deformation
Deformation of a material that will remain permanent after removal of the load which caused it.

Quenching
A process of rapid cooling from an elevated temperature by contact with liquids, gases or solids.In the heat treating of steel, the step of cooling metals rapidly in order to obtain martensite by immersing or quickly cooling the steel in a quenching medium. The quenching media may be water, brine, oil, special solutions, salts or metals; and the intensity of the quench is determined by the temperature, volume and velocity of the media. In the case of air hardening tool steels the quenching medium is air at room temperatures.

Reduction of Area
The percentage difference between the original cross sectional area and that of the smallest area at the point of rupture. The percentage figure can be considered a measurement of ductility.

Residual Stress
Macroscopic stresses that are set up within a metal as the result of non uniform plastic deformation or thermal gradients. Stresses of this nature are caused by cold working or by drastic gradients of temperature from quenching or welding.

Rimmed Steel
Low-carbon steel in which incomplete deoxidation permits the metal to remain liquid at the top of the ingot, resulting in the formation of a bottom and side rim of relatively pure iron of considerable thickness. Steel products such as sheets produced from this type of ingot will have a very good surface quality free of surface defects.

Rockwell Hardness
A method of measuring the hardness of materials (resistance to penetration). Rockwell measures the hardness by pressing an indentor into the surface of the steel with a specific load, then measuring how far the indentor was able to penetrate. There are a number of Rockwell tests the most common is Rockwell B.

Rolling
A term applied to the operation of shaping and reducing metal in thickness by pressing it between rolls which compress, shape and lengthen it following the roll pattern. Steel is either hot rolled or cold rolled depending upon the product being manufactured,

Scale
A complex iron oxide formed on the steel surface during the hot rolling operation or formed on steel parts which are heat treated in the presence of oxygen.

Semikilled Steel
A commonly used grade of steel manufactured for low carbon bars and structurals. A steel is considered semi killed when it is produced so that it is incompletely deoxidized and it contains sufficient dissolved oxygen to react with the carbon to form carbon monoxide to offset solidification shrinkage in the ingot.

Stainless Steel
Corrosion resistant steel of a wide variety, but always containing a high percentage of chromium. The minimum chromium content is considered at 11% for stainless steel, although lesser amounts of chromium are found in stainless products such as those used for automobile mufflers. Stainless steels have the properties of being highly resistant to corrosion attack by organic acids, weak mineral acids, atmospheric corrosion, etc. Some standard grades of stainless steel also have 3.5 to 22% of nickel which further increases resistance to chemical and atmospheric corrosion.

Steel
A solid solution of iron and carbon. An iron-base alloy, malleable in same temperature range as initially cast, and containing carbon in amounts greater than .05% and less than about 2.00%. Other alloying elements may be present in significant quantities, but all steels contain at least small amounts of manganese and silicon.

Strain
Deformation produced on a body by an outside force.

Stress Relieving
A process of reducing residual stresses in material by heating to a suitable temperature and holding for a sufficient time. this treatment may be applied to relieve stresses inducted by casting, quenching, normalizing, machining, cold working or welding.

Temper
The state of or condition of a metal as to its hardness or toughness produced by either thermal or heat treatment and quench or cold working or a combination of same in order to bring the metal to its specified consistency. A condition produced in a metal or alloy by mechanical or thermal treatment and having characteristic structure and mechanical properties.

Tensile Strength
The maximum load in pounds per square inch that the sample will carry before breaking under a slowly applied gradually increasing load during a tensile test. The ratio of maximum load to the original cross-sectional area.

Tool Steel
Actually, any grade of steel that can be used for a tool. Generally the term tool steel as applied in the steel industry is a grade of steel characterized by high hardness and resistance to abrasion coupled in many instances with resistance to softening at elevated temperatures. These properties are attained with high carbon and high alloy contents and the steel is usually melted in electric furnaces to assure cleanliness and homogeneity of the product.

Toughness
The ability of a metal to absorb energy and deform plastically before fracturing. It is usually measured by the energy absorbed in a notch impact test such as the Charpy or Izod Impact Test. The area under the stress-strain curve in tensile testing is also a measure of toughness.

Ultimate Strength
See tensile strength.

Water Hardening
High carbon grades of tool steel, straight carbon steels and low alloy steels that are hardened by quenching in water during the heat treating operation.

Work hardening
An increase in resistance to deformation (hardness and strength) caused by cold working.

Yield Point
The yield point is the load per unit area at which a marked increase in deformation of the specimen occurs without increase of load during a tensile test.

Yield Strength
The point at which a material exhibits a strain increase without increase in stress. This is the load at which a material has exceeded its elastic limit and becomes permanently deformed. Stress corresponding to some fixed permanent deformation such as .1 or.2% offset from the modulus or elastic slope.

Young's Modulus
Same as modulus of elasticity.

Section 13 - Sources and Notes:

The following are related Steel links and resources.

Iron and Steel Industry - Compton's encyclopedia on the history of iron and steel origins, production and modern industry.

Ryerson Tull - supplies industry with more than 100,00 items of steel, stainless steel, aluminium etc. material. Check here for local distributors and stock list.

American Steel and Iron Institute - AISI organization.

International World Steel Organization - Good general and informational resource.

The Engineer's Edge - Engineering data and information

Engineering Fundamentals - Engineering data and information (limited free info, pay site)

The Steel Tubing Institute of North America - The web site of the folks that make the stuff

Metal Info.com - lookup and cross reference steel specifications (limited free info, pay site)

Pirate4x4 Tech Reference Section - all kinds of info maintained by yours truly.

Seaport Steel Co. - A Steel company with some tech info on their page

Thompson Metals and Tubing Co. - Another company with tech info on their pages.

Notes:

[1] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.49

[2] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.45

[3] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.44

[4] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.53

[5] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.63

[6] "Machinery's Handbook" 24th Edition. Erik Oberg, Franklin D. Jones, Holbrook L. Horton, Henry H. Ryffel, Robert E. Green; Industrial Press Inc., 1992 p.381

[7] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.63

[8] "Machinery's Handbook" 24th Edition; "Engineer to Win". Carroll Smith; http://www.engineersedge.com/ ; http://www.efunda.com/

[9] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.60

[10] http://www.steeltubeinstitute.org/dom.htm

[11] "Engineer to Win". Carroll Smith; Motorbooks International, 1985 p.62

[12] "Machinery's Handbook" 24th Edition. Erik Oberg, Franklin D. Jones, Holbrook L. Horton, Henry H. Ryffel, Robert E. Green; Industrial Press Inc., 1992 p.272

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- Part 1a - The Tech Behind the Talk - Steel and Material Strength
- Part 1b - The Tech Behind the Talk - Axle Shaft Technology
- Part 2 - Superior Shafts and CTM Joints
- Part 3 - Polyperformance Drive Flanges
- Part 4 - Crane High Clearance Knuckles, Steering Arms, and Diff Cover
- Part 5 - Selectable Locker
- Part 6 - Testing and Summary

Contact Info:

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