4130 in frame building

kuromori

4130 (25crmo4) is a type of chromium-molybdenum steel (crmo, cromo, chromoly, etc.) which is the most commonly used alloy steel used in steel bicycle frame manufacture. It is typically supplied normalized and stress-relieved state (Reynolds 520/525, Columbus Cromor/Zona, Tange Champion, Dedacciai BKS, Variwall Chromoly CMH, NOVA CRMO, Kaisei CR-MO black label, etc.) but also available in "heat-treated" (quenched and tempered) form (Reynolds 725, Tange Prestige/Ultimate, Dedacciai HTS, Variwall Chromoly CMD, Kaisei Ultima blue label, etc.). While seamless tubing was a common mark of quality cycle tubing of yesteryear, fewer brands have chosen to explicitly state that their tubes are seamless (Columbus Zona only, Tange Prestige/Ultimate only, etc.) with the assumption that others are seam welded DOM. While seamless tubing used to be considered important and the sign of quality cycle tubing, the quality of modern seamed tubing is more than sufficient for frame building, and generally considered of only minor importance.

The use of 4130 in the construction of bicycle frames presents unique challenges not typically found in the construction of other 4130 parts or assemblies. Quality 4130 frames are made from very thin tubing, in the range of 0.4-1.0mm, and are commonly brazed, not just fusion welded. Further standard references for metals are often based on idealized and well controlled parameters, unlike in actual fabrication. While decades of practical application and experience show there are many ways to build a steel frame that will last a lifetime, some frame builders seek to push the limits, experiment with new styles, designs, and techniques, or wish to build the best frames they can. However, the explanations offered by frame builders and cycling experts for the suitability or superiority of their construction techniques are often dubious or contradictory, and the common wisdom in frame building is simply more heat, more bad.

A Primer on Metallurgical Terminology

A common problem in metallurgical discussion and explanations surrounding metal frame materials is that terminology is often misused or misunderstood. Many of these properties are interrelated and well correlated with each other, but are not the same.

Hardness – Resistance to localized plastic deformation due to indentation. It is usually given in Rockwell C (HRC), Brinell (HB), or Vickers (HV5) for steels. In reference to metals it almost always means indentation hardness, not scratch hardness, such as the well known Mohs hardness scale. Because it tests for plastic deformation, it is obviously related to yield strength, but also related or proportional to things like fatigue resistance and UTS. Increasing the hardness and strength of steel involves some process that increases the density of dislocations, or otherwise distorting the lattice so that mobility of dislocations is limited. It is not a particularly useful metric for the frame builder nor especially important in bicycle frames as other frame materials are often softer. It has some correlation to ease of machining and cutting, but even then it not a strict one-to-one correlation. It is generally favored in metallurgical study because it is useful as a proxy since it correlates well to characteristics we care about, and can quickly be measured at multiple points on a sample, and samples do not have to conform to standard shapes and sizes used in other tests.

Yield Strength (YS) – The amount of force before permanent (plastic) deformation occurs. It is usually given in MPa (megapascals or N/mm^2) or some other unit of force per area, such as PSI (pounds per square inch) or tons (tons per square inch). It tends to be correlated with hardness. Some frame builders will say this is the only strength that matters because a bent frame is a ruined frame and UTS is unimportant because a frame bends before it breaks. In respect to frame building, yield strength reflects the amount of force, and therefore deflection, required to permanently bend, indent or cold set a tube, as well as representing dent resistance.

Ultimate Tensile Strength (UTS) – The amount of force before fracture occurs. It is usually given in MPa (megapascals or N/mm²) or some other unit of force per area, such as PSI (pounds per square inch) or tons (tons per square inch). It tends to be correlated with hardness. Some frame builders will say this doesn't matter because a bent frame is a ruined frame and UTS is unimportant because a frame bends before it breaks. For non-precipitation hardening steels (so excluding proprietary Columbus alloys), and hardness less than 400 HB, which 4130 generally falls into, one half of UTS is often used as a proxy for the fatigue limit. In respect to frame building, UTS is a proxy for estimating fatigue resistance.

Toughness/Brittleness – Toughness and brittleness are opposites of each other. Toughness is the ability to absorb energy and plastically deform without fracturing. It tends to be inversely correlated with hardness. It is related to the area under the stress-strain curve. Since Young's modulus is essentially constant for steel, the area under the elastic part of the curve is proportional to yield strength. The component of toughness from the area under the curve past the yield point represents plastic deformation, and therefore frame failure, but not fracture, or catastrophic frame failure. Brittleness is often caused by intergranular effects weakening the steel between grain boundaries. An example of catastrophic frame failure would be the head tube joints cracking, causing the head tube and fork to separate from the frame. In respect to frame building, brittleness is susceptibility to cracking due to a large impact, and because brittleness presents a large risk of bodily harm, great care must be taken not to embrittle the frame.

Ductility/Elongation – Ductility is the ability to plastically deform without fracture. It is either represented in percent reduction of area, or percent elongation when a sample is subjected to tensile force, with higher percentages meaning increased ductility. It tends to be inversely correlated with hardness. In respect to frame building, yield strength reflects the degree a tube can be permanently bent, indented or cold set.

Grain – The microstructure of steel forms granular crystals in random orientations, with finer grain generally being preferable. Not to be confused with "grain" from forging, in which non-metallic inclusions or impurities are elongated and reduce strength and fatigue resistance transverse direction in addition to possible grain manipulation. While the grain can be manipulated and elongated with cold work, steel will recrystallize and form new grain when heated. The minimum temperature at which this starts depends on the state of the steel, but it will always occur at A1 (742C). This has no effect on the inclusion part of forging "grain." Fracture is often transgranular (through the grain) but can be intergranular (between grains) when the grain boundaries are weakened. In respect to frame building, the cold worked grain structure should be preserved as much as possible in the case of silver brazing and grain growth should be prevented when brass brazing by minimizing temperature and time brazing when possible within the limits of the joining method.

Cold Work – Plastic deformation that occurs below the recrystalization temperature. Depending on the way the steel is deformed, it compresses the grain in one or two axes, and causes elongation in one or two of the other axes. This causes steel to exhibit different strength along different axes, but this is relatively unimportant to the frame builder. Cold work is likely a reason why drawn steel tubes often show higher strength than data sheets for normalized 4130 would show, as cold drawing is a cold working process. Cold work induces work hardening and increases strength but decreases ductility, however it also lowers the temperature at which steel starts to recrystalize, even at silver temperature and below, which undoes the effects of cold work. In respect to frame building, since tubes are cold drawn, they are susceptible to recrystalization and weakening, meaning that to preserve the cold worked grain structure, minimizing temperature and time at temperature should be minimized as much as possible within the limits of the joining method.

Residual Stress – Stresses (forces) that remain in the steel, often due to cold work or the uneven expansion and contraction of the steel caused by heating and cooling. From the factory this happens during drawing and quenching, and tubes are stress relieved by heating as a result. Although it is often assumed to be bad, compressive residual stresses at the surface can increase fatigue life, but tensile ones decrease it.

Unknown residual stress has the potential to cause frame failure, so stress relieving is generally safer than not. It also happens as a result of the frame building process whenever a tube is plastically deformed, or tubes are unevenly heated. Some frame builders feel that "witch-wanding" or heating one side of a tube then allowing it to contract to bend it for alignment does not impart residual stress, but it obviously does. In respect to frame building, unintentional residual stresses should generally be avoided, but surface finish involving shot peening may increase fatigue life.

Stiffness – The relationship between stress and strain in the elastic range, usually given as Young's modulus or the modulus of elasticity. It is essentially the same for all steels, so that all frames made of steel to the same dimensions will deflect the same amount for a given amount of force, given that the deformation is elastic. In respect to frame building, this means alterations in stiffness must be made by changing the shape of the frame in some way, often through the change of wall thickness or tube diameter, but also through the use of shaping and reinforcement.

Damping – Damping capacity is the ability of steel to convert mechanical energy to heat. Damping is not the same thing as stiffness. It is usually given as specific damping capacity. The damping ratio is affected by many factors such as application, amplitude, alloy and microstructure. Damping is given credit for reducing "road buzz" and energy loss due to lack of stiffness, however steel frames are also often assumed to operate as efficient springs with the body and tires providing most of the damping. The effect of frame damping is unknown in frame building, however it provides a possible explanation of "dead" hi-ten frames or cooked tubes, or "buzzy" frames that can not be explained by any difference in stiffness. Some experts involved in the cycling industry have asserted this, while others mistaking stiffness for damping, have dismissed them because stiffness is equal. Again, it is unknown if damping plays any significant or noticeable effect in steel frames. In respect to frame building, this means a frame builder should not say frame flex equates to increased damping, and perhaps keep an open mind that ride quality may not be identical between steels even if stiffness is identical.

Fatigue Resistance – Fatigue is the weakening of metal from repeated cyclic stresses that eventually causes cracks to propagate and grow. Fatigue resistance is affected by numerous factors. Some "experts" and frame builders are quick to point out steel has a "fatigue limit," and stresses below that limit do not fatigue the steel, therefore steel frames do not fatigue. Some others even more erroneously claim that the fatigue limit is the same as the elastic limit, because they think bending a paper clip back and forth until breakage is a demonstration of fatigue and not work hardening.

The elastic limit is not the same as the fatigue limit, and the fatigue limit is lower. Steel has no fatigue limit in corrosive environments, and some steels have been demonstrated to suffer from corrosion fatigue even in humid air. Unusually high stresses during riding may be high enough to exceed the fatigue limit even if loads from normal pedaling fall below the limit. Heat severely reduces the strength of steel, and it is fair to assume that fatigue strength in those areas is also compromised. Stress risers also help in local crack formation by increasing stresses beyond the fatigue limit, so even if most of the frame does not see stresses that exceed the fatigue limit, some parts of the frame may. Fatigue resistance has long been a concern of cycling tubing makers, and countless steel frames have failed due to fatigue.

Traditional frame building methods have proven to produce frames that are capable of lasting a lifetime when not ridden excessively hard or built sufficiently strong. Frequently a frame will fail from some other exogenous damage before it can fail in fatigue. However it is not safe to assume that steel will not suffer from fatigue just because it is steel. Frame building practices likely have a significant effect on fatigue resistance, and fatigue resistance is a chief concern in building a durable long lasting frame. A frame with sufficient fatigue resistance will also be strong enough not to fail from normal use. Since building a frame that can survive extreme abuse is often infeasible, or the associated characteristics (e.g. weight and feel) of overbuilding a frame may be undesirable, so a well built frame will be built around balancing fatigue resistance with other design criteria.

Frame Failure, Fatigue, and Buckling

Some frame builders feel that yield strength is important while ultimate tensile strength is not, since YS is lower than UTS, so YS makes frames more damage resistant in the form of dent resistance, and a frame that fails due to breaking has already failed due to yielding. However typical frame designs already have sufficient YS for normal use, and only need reinforcement for extreme abuse. Designing around YS neglects fatigue resistance, meaning the frame will be short lived if subjected to frequent relatively high loads, and it is often impractical to design frames to survive abuse like crashing into walls, surviving collisions with automobiles, or bad crashes in general.

It is perhaps worth noting that while quality cycle tubing is typically cold-worked or heat-treated, increasing both YS and UTS, brazed areas and surrounding HAZ do not share the characteristics of the tube as delivered. In this case, annealed tubing when compared to normalized tubing has superior YS (460 MPa vs 435 MPa) but inferior UTS (560 MPa vs 670 MPa). Thus, if the frame builder is worried about the frame surviving very rare but extreme abuse, or only surviving for a short event, then annealed 4130 technically has higher YS, but it would be much more prudent to simply use heat-treated 4130 or some other high end alloy which would result in superior YS and UTS.

Other frame builders have cited a preference for non-heat-treated tubes thinking they offer increased fatigue resistance since fatigue manifests in cracking, and cracks are associated with brittle failure. Ductility can help in fatigue resistance, but this normally applies to cyclic stresses in excess of yield strength resulting in plastic deformation (like breaking a paperclip). Frames generally are designed not to exceed yield strength, and yield failures are often not cyclic in nature, making ductility not particularly useful for increasing fatigue life in this application.

For non-precipitation-hardening steels under ~1350 MPa (400 HB), half of UTS is used as a proxy for the fatigue limit when it is not empirically and destructively tested. Because the side affects of heat are incidental in frame building, not intentional heat treatments, specific fatigue testing can only be done comparatively. For those skeptical of the relation between UTS and fatigue resistance, note that fatigue failure is the result of cracks, and these cracks form under tensile stress. Even though UTS is not exceeded, one can note some similarities between the modes of failure.

In no particular order, fatigue failures are common at the base of the seat tube, at braze-ons, at the chainstays near the BB, bridge or indentations, the driveside dropout connection to the chainstay, the HT/DT lug area, the ends of the HT especially the bottom, the seatpost clamp slot and the narrow point of a side tacked seatstay. Thus the goal of frame design in designing a fatigue resistant frame is attempting to increase strength and reduce tensile stress in these areas.

Residual stress… (WIP). Residual stress can effectively increase or decrease tensile strength. Without knowing how to impart compressive residual stress to counter tensile stress, reducing residual stress is generally better because will most likely strengthen the weakest link. Residual stress can be reduced by minimizing differential rates of expansion and contraction, avoiding plastic deformation (bending/cold setting) and stress relieving by heating to temporarily reduce the yield strength of the steel. These must be balanced with other frame building considerations.

While crack formation occurs under tensile loads, (elastic) buckling occurs under compressive loads. In theory, it has no relation to any property of steel tubing except for the shape (diameter and wall thickness), modulus of elasticity (which is essentially constant for steel) and imperfections which are primarily design considerations rather than production processes. UTS and YS are irrelevant, although elastic buckling can lead to inelastic buckling when yield strength is exceeded. Buckling should be avoided because behavior is relatively unpredictable when buckling occurs. It is commonly accepted that risk of buckling/crippling can be ignored when the diameter exceeds 50 times the wall thickness (Maddux, 1969), or 0.5mm for 25.4mm, ~0.6mm for 28.6/31.8mm, 0.7mm for 34.9mm, based on a rule of thumb for axial loading. However this is of questionable usefulness in framebuilding as only seatstays and the driveside chainstay see signifigant axial load (Peterson and Londry, 1986). It is also just a rule of thumb, an in practice tubes in bending often only buckle after yielding (Karamanos, 2011). Furthermore, it is known that theoretical calculations often don't translate well into practical results when it comes to buckling.

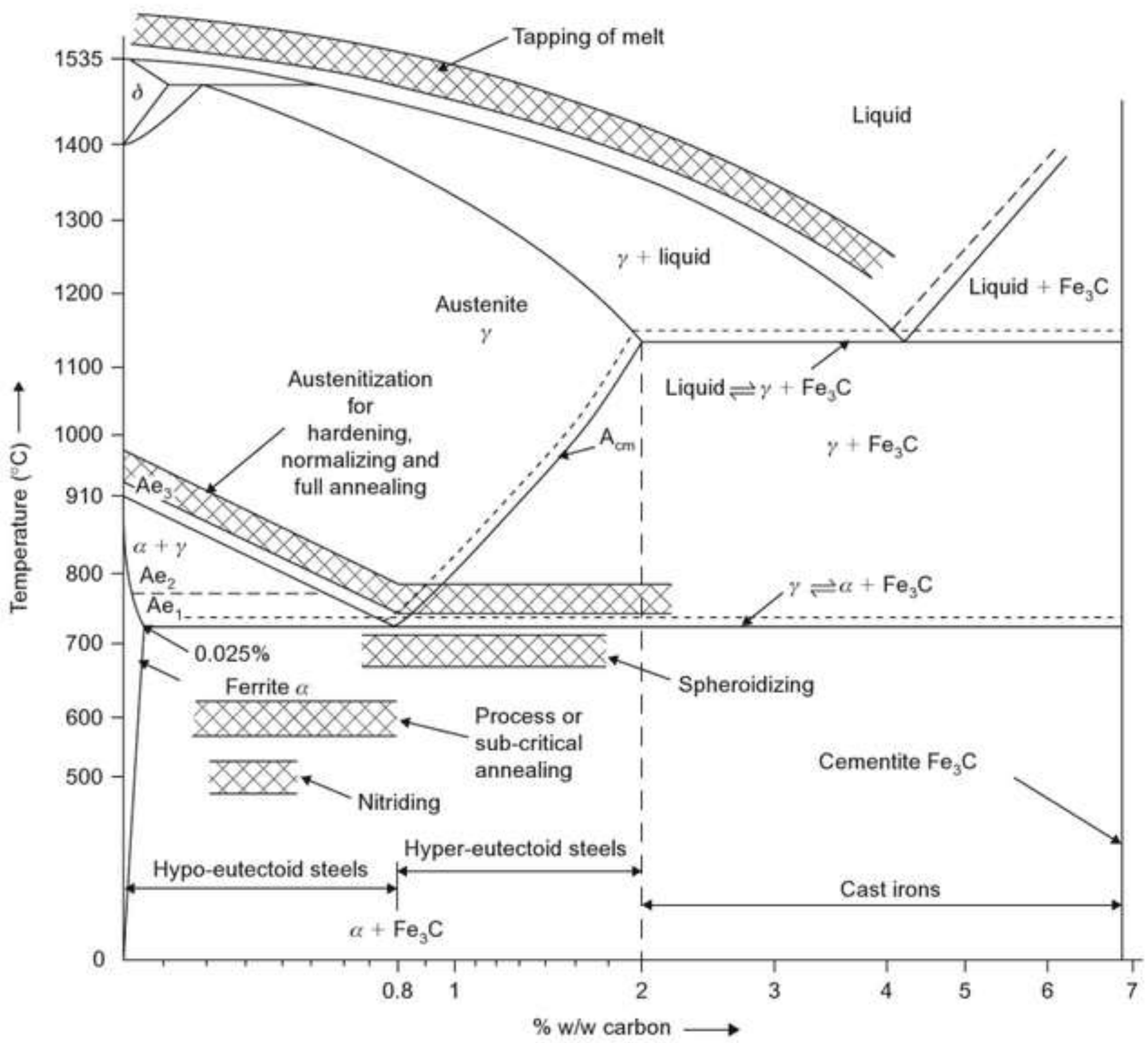
Buckling failure appears to result from front end crashes almost exclusively, where a signifigant bending load is transmitted through the fork to the headtube. Practical experience bending tubes tends to show that a tube will yield before buckling occurs resulting in a crinkled tube. Lugs also seem not to help, as either due to annealing or stress risers, tubes tend to bend near the lug, whereas on welded frames there might be a small amount of bending in the HAZ, but the buckling will occur mostly at the butt transition area. Stronger steel may offer improved resistance to this kind of permanent yield failure, especially increasing strength at the weakest link. Reducing stress by increasing cross sectional area or altering the diameter:wall ratio may also help. Design in resisting crash damage requires empirical study, or may be ignored as impractical to build a frame around.

It must be emphasized that a steel tube of a given dimension under a certain force will always buckle/cripple, even if it has infinite tensile and yield strength. In such a case, the tube would wrinkle under load, then spring back to round. Increasing the strength of steel has no effect in reducing elastic buckling/crippling. Elastic buckling/crippling of a steel tube is a function of its geometry. What increasing strength does is it increases yield strength. If elastic buckling/crippling does in fact occur (which I am skeptical of), then increasing strength will possibly prevent yielding and allow it to spring back. Otherwise, increasing yield strength helps it resist yielding which, once the steel yields, the stress:strain ratio (modulus of elasticity is also stress:strain) lowers and the tube is no longer straight, causing it to buckle/cripple and remain permanently bent.

For a typical steel frame, it is questionable if the 50:1 rule has any significant meaning for this application besides being a known safe value. Some cycle tubes have a diameter to wall ratio of ~100:1. It is likely that a frame will suffer yield failure before buckling, but buckling after yield failure may result in extreme yield failure that makes the frame unrideable. Even though strength has no effect on elastic buckling, increasing tube strength or decreasing stress may still improve the frame's resistance to failure modes associated with buckling, as buckled frames failed in yield and likely yielded even before buckling. Experiments applying static loads to frames and observing if there is elastic buckling would greatly aid in determining if there is a point to considering buckling in frame design.

(Air)Hardening of 4130

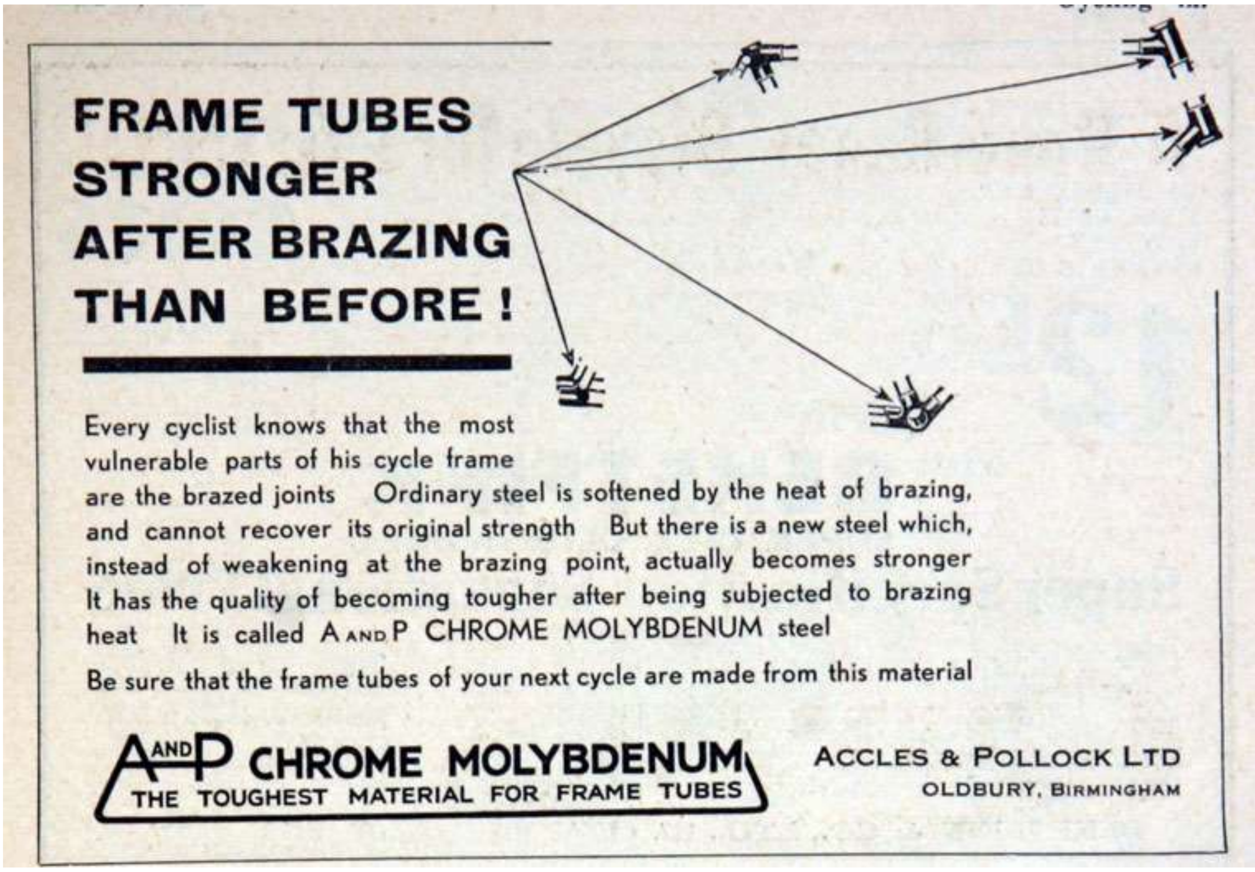
Hardening 4130 generally first involves heating the steel up past A1 (742C) where the microscruture starts changing to austenite, above A3 (826C) to allow for the full transition to austenite. As the steel cools from there, the austenite has a tendency to form different microstructures at different temperatures over time. To prevent this, the tubes are rapidly cooled by quenching in either water or oil, until the steel reaches Ms (martensite start) temperature where any austenite that hasn't transformed into a different microstructure yet starts forming martensite, and continues forming martensite as the steel cools to Mf (martensite finish). After quenching the steel is martensitic instead of pearlitic at room temperature as shown on the phase diagram. However martensite is very brittle and the steel has a considerable amount of residual stress and must be tempered before it is usable. In the case "heat treated" (quenched and tempered) Reynolds 725 the tubes are heated to 865C, soaked for 30 minutes, then quenched in oil (Lynch and Jannetti, 2010).



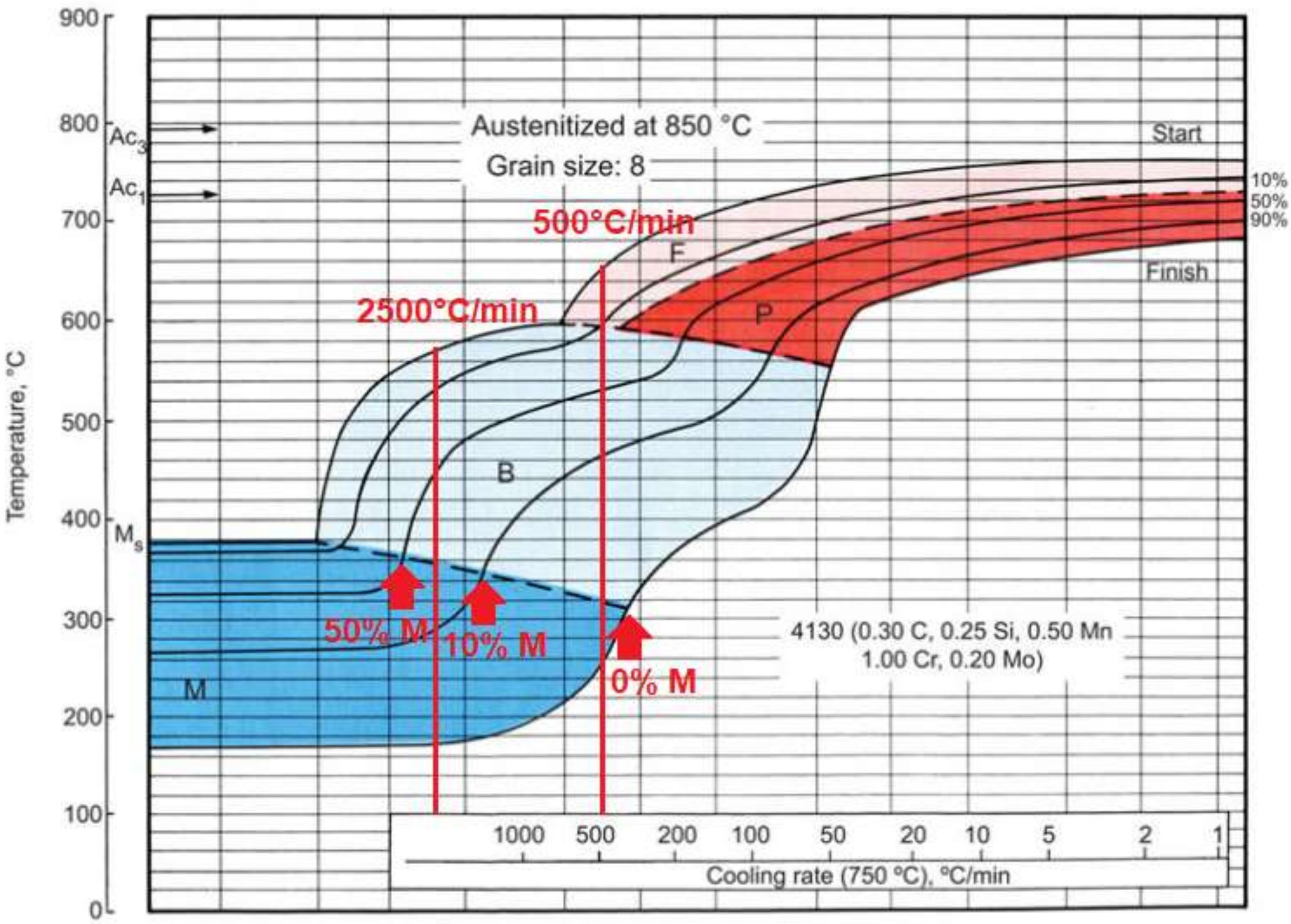
From: Modern Physical Metallurgy by Smallman and Nagan

4130 is typically not considered to be an air hardening steel, and in most applications, that would be accurate. However, it is generally understood that even if not quenched in water or oil, parts of the HAZ of a 4130 weld can harden and develop martensite which causes localized hardness and embrittlement. This is because of self-quenching where the surrounding metal acts as a heat sink which increases the rate of cooling of the weld that results in localized quenching. It is likely something similar can also occur in brass brazed which reaches temperatures above A3 at ~850C, but not silver brazed 4130 which is brazed at lower temperatures.

Estimating a wide ball park estimate of continuous cooling rate in the range of 500C-2500C per minute, based loosely on the time it takes for a joint to air cool from brazing temperature until it stops glowing, I would guess that a joint raised to brass brazing temperatures then allowed to air cool transforms into mostly strong bainite (B) with some fraction of even stronger but brittle martensite (M) less than 50% closer to ~10%. Bainitic steel is tougher than matensitic steel for the same hardness, and bicycle frames do not need the high potential hardness martensite offers, making bainitic microstructure very suitable for bicycle frames.

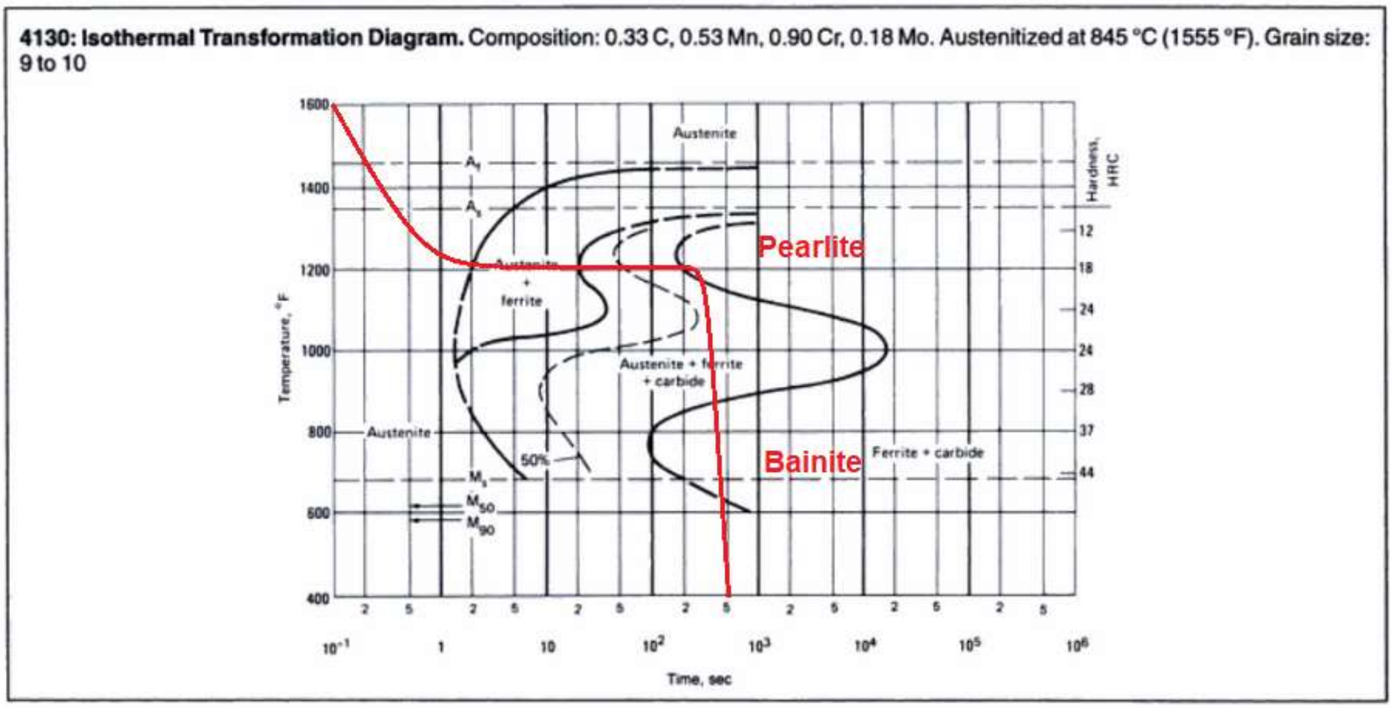


An advertisement circa 1931 for A&P KROMO



Original from ASM International

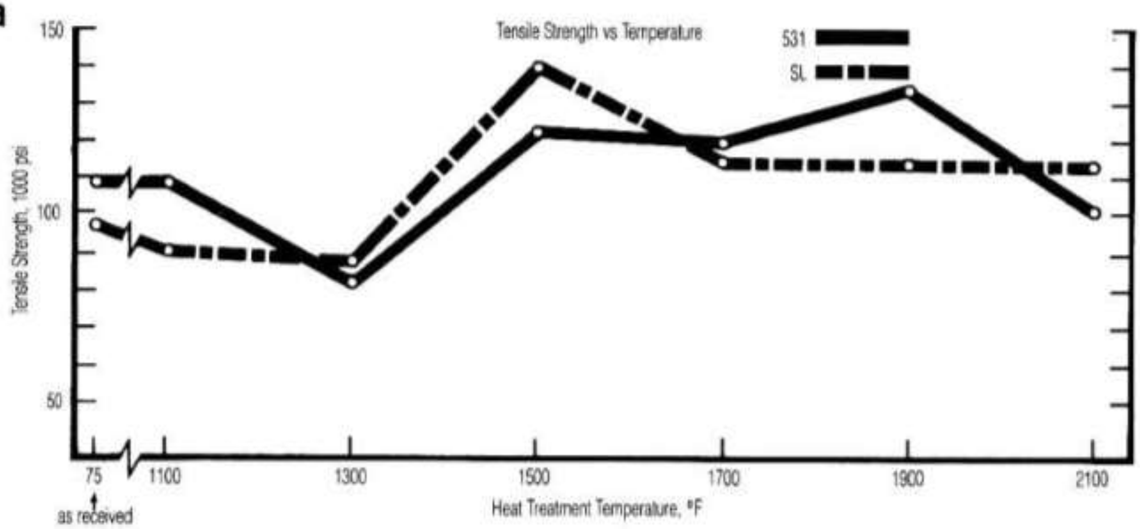
However if the steel is not allowed cool at a constant rate, and cooling rate is reduced, for example, dropping from 1600F (871C) to 1200F (649C) over 30 seconds, then kept at 1200F (649C) for another 90 seconds, then cooled to room temperature, the austenite will transform into soft and weak pearlite (the upper nose of “Ferrite + carbide”) and not transform into anything else as it cools.



Original from ASM International

The air hardenability of 4130 cycle tubes is supported by experiments on actual cycle tubing. There appears to be at least a moderate hardening effect because of the high rate of cooling caused by the relatively high surface area to thermal mass ratio of cycle tubing. Thin wall tubes of 25crmo4 cycle tubing (marked SL, different from modern production Columbus SL) were shown by Emiliani (1983) to increase in tensile strength when heated to brass brazing temperatures of 1700F (927C) for 5 minutes compared to the steel as delivered, as well as at 1500F (816C) which is at the upper end of the intercritical range. At the very least, normalization restored strength to the steel, in excess of the as delivered condition and over the dip in strength when heated to lower temperatures. Note that the author explicitly states that the lines between data points can not be used to interpolate. Excessive temperatures and cycle times may result in unwanted grain growth and the tubes still should not be heated beyond what is neededto braze.

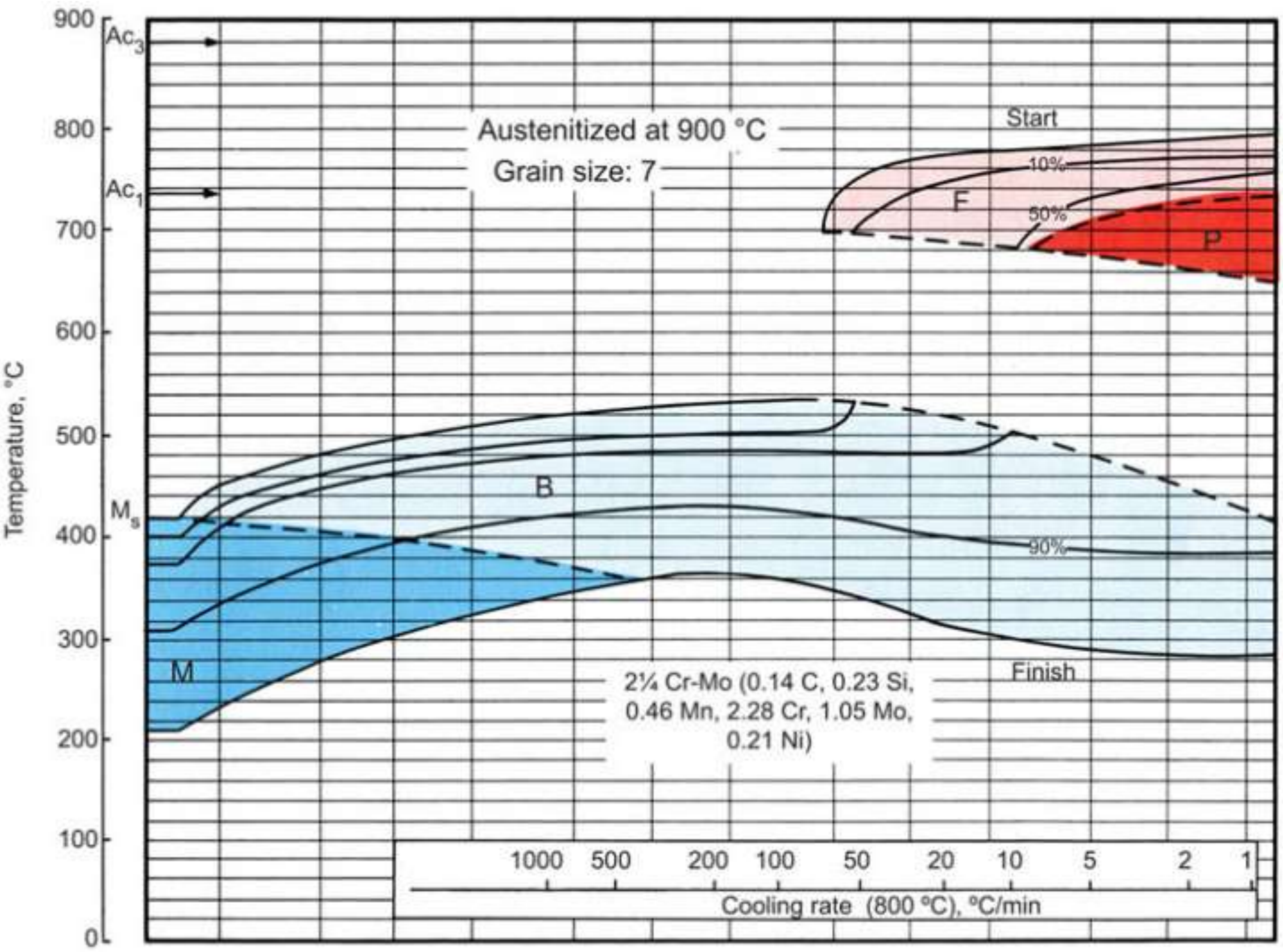
Figure 4a



(**Emiliani, 1983)**

Columbus (1987) has also shown the hardening effect with localized heating (850C at 4 minutes), such as that which occurs when brazing. The micrograph for the point with hardness of 350 HV (bottom right) shows dual phase ferrite-martensite, indicating that this point was likely heated to intercritical temperatures (between A1 and A3, ~742-826C). Dual phase ferrite-martensite is not of high concern, as is it strong while the ferrite lends high ductility offsetting the brittle nature of martensite. More concerning is the microstrcture where the steel was fully austenitized with the potential to form brittle martensite. Presumably higher temperature points to the right which also hardened formed bainite and some martensite, but most likely with a martensite fraction less than 50% based on hardness, resulting in steel that is strong but not excessively brittle. While 4130 could be hardened further with forced air cooling, this is explicitly not advised due to the increased brittleness of an increased percentage of untempered martensite.

While 4130 can sometimes harden in air, forming strong bainitic and martenistic structures, it is not in the same class as air-hardening alloys. 2 1/4 steel is generally not considered an air-hardening alloy the way tool steels such as A2, which is meant to fully transform austenite to strong and brittle martensite when air cooled (not shown), are, but these types of steels are very brittle as-quenched and require tempering so are only suitable when very high hardness is needed. Instead 2 1/4 is shown because of the large window of cooling rates in which it forms 90%+ bainite, from ~50-4000C/min, meaning formation of weak pearlite or excessive brittle martensite is unlikely. There is a much narrower, but still achievable band to obtain bainite formation with 4130. Technically, there is more than one form of bainite, but bainite in general is considered to perform favorably compared to pearlite and comparably to tempered martensite found in "heat treated" (quenched and tempered) tubes for this kind of application, but without the need for quenching or tempering. Some descriptions of some cycling tubes mention bainite, and I suspect these may be austempered to form bainite.



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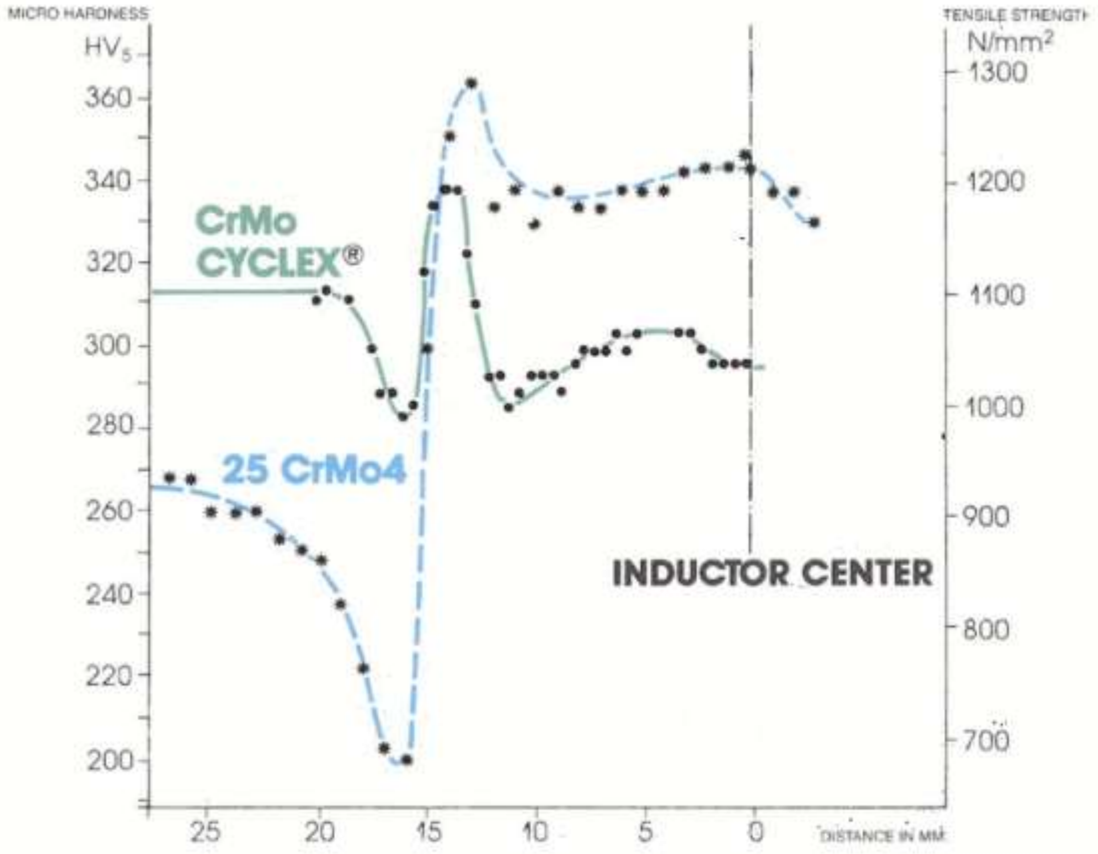


25 CrMo4:
UNALTERED STRUCTURE

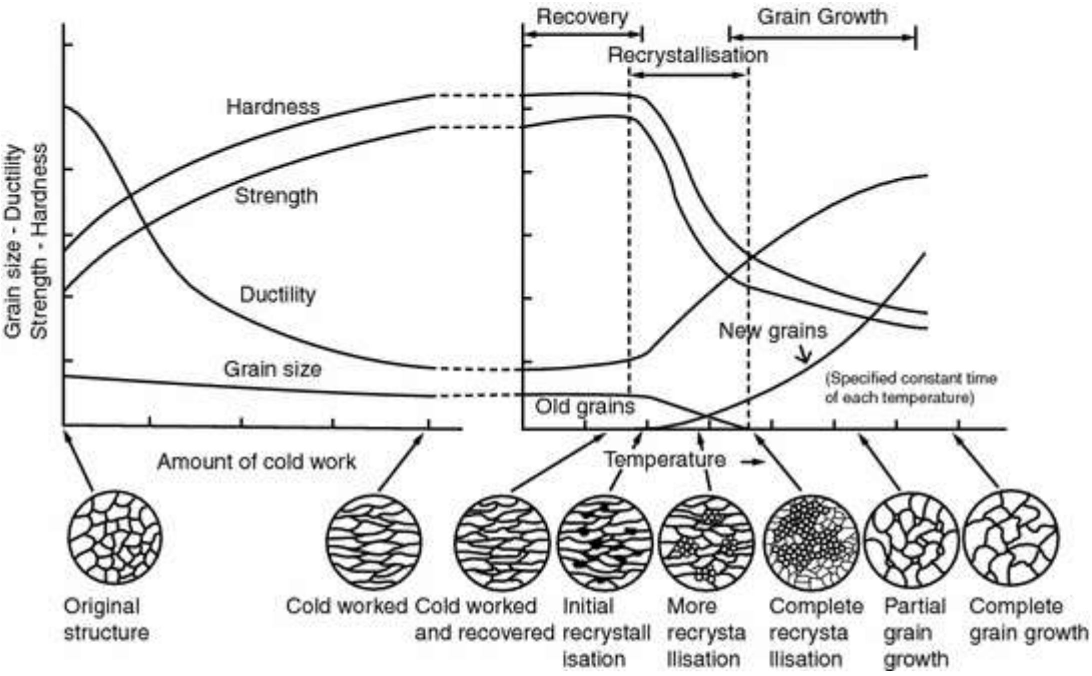
25 CrMo4:
RECRYSTALIZED STATE (200 HV_5)

25 CrMo4: FERRITE-MARTENSITIC
STRUCTURE (350 HV_5)

Although not typically considered an air hardening steel, nor in the same class as air hardening cycle tubing (Reynolds 853, Vari-Wall THERMLX, Fairing Velospec etc.), based on experiments performed by Emiliani and Columbus, 4130 brought to brazing temperature and allowed to air cool appears to partially harden or increase in hardness when used in thin wall cycle tubing, or when locally heated such as when brass brazed or welded. However, brazing techniques that slow the rate of cooling may prevent this effect from occurring, especially if held at temperatures where pearlite forms. It may be noted that hardness, used as a proxy for yield strength, did not increase past the values for the tubing as delivered. One explanation is that yield strength doesn't track UTS well when crossing the through intercritical temperatures (between A1 and A3, ~742-826C) due to the changes in microstructure occurring there.

Annealing and Recrystallization

Annealing is a heat treatment that decreases hardness and increases ductility, however this term is often used to refer to full annealing, a specific kind of annealing meant to make the steel as soft and easy to work as possible, which has little relevance to frame building. Annealing in reference to frame building is largely unintentional, and the product of adding heat during the joining processes. Some refer to the annealing of steel below critical temperature as tempering out of convenience, because the process is the same and macroscopic effects on material properties are similar, and it is indeed easier to think of them as the same sort of processes. Recrystallization in this case is annealing that occurs when cold worked microstructure with elongated grains is heated, which causes new ferrite grains to form that replace the cold worked ferrite grains, lowering strength and returning it to a state similar to how the steel was before cold work.

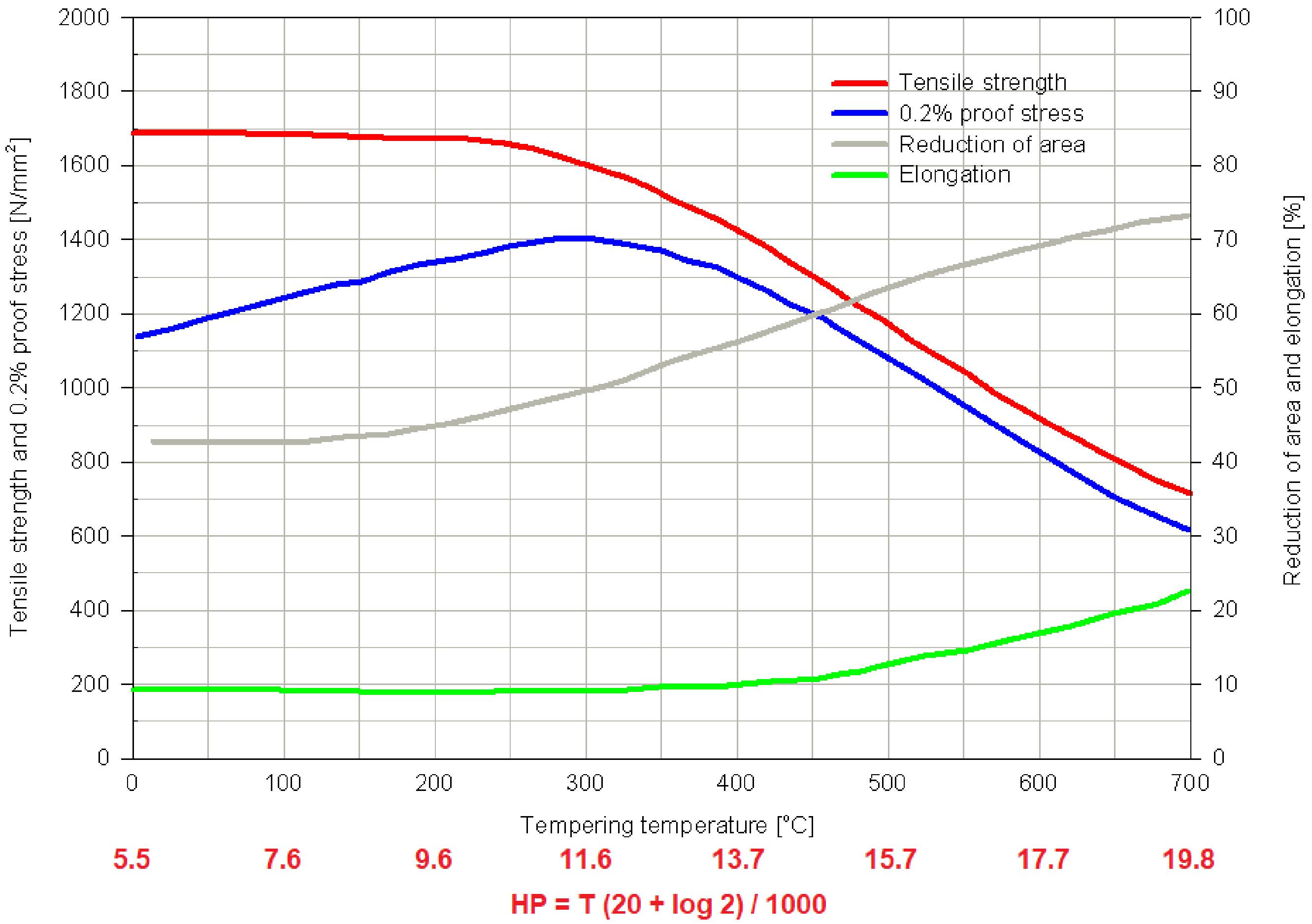


Cold-drawn cycle tubing often has higher UTS values than typical for normalized 4130 which usually attributed to work hardening. Columbus (1987) attributes the loss in strength due to subcritical (less than 742C) heat to recrystallization of the as delivered microstructure. The point with the minimum hardness of 200 HV (bottom middle) shows the recrystallization of the steel where the original cold worked structure with elongated grains was replaced with a new grain structure. Hardness and UTS drop from the elevated work hardened levels to levels closer to typical normalized 4130. This effect happens at subcritical temperatures (less than ~742C). Quenched and tempered “heat-treated” 4130 is likely recrystallized as part of the post-drawing heat treatment and instead undergoes tempering. Recrystallization is a function of several variables, especially the amount cold work done, meaning there is no generalized fixed temperature for 4130. These variables also include temperature and time, meaning brazing time and temperature should be kept to a reasonable minimum, but not to the point where it introduces other problems.

Tempering

Tempering is another process of applying heat to to reduce hardness and increase ductility. The difference is tempering is heat applied to quenched steel which was cooled fast enough that it formed martensite. Bainite can also be tempered, but is considerably less sensitive relative to martensite. Tempering is especially important since quenched steels tend to be brittle and have high internal stresses.

When purchasing “heat treated” 4130, temper is part of the heat treatment performed by the manufacturer. The intricacies of quenching are conveniently ignored because it has no importance to the frame builder. Briefly, the 4130 is heated to ~850C, changing the microstructure and forming austenite. As it is cooled from critical the austenite will want to transform into other structures, but if cooled rapidly enough, it can not until any austenite still remaining in the steel starts transforming at ~350C into martensite, and continues transforming into martensite as it cools. This martensite is hard, strong and brittle. Reheating the steel again, but not as high, tempers it, changing the physical properties of the steel.



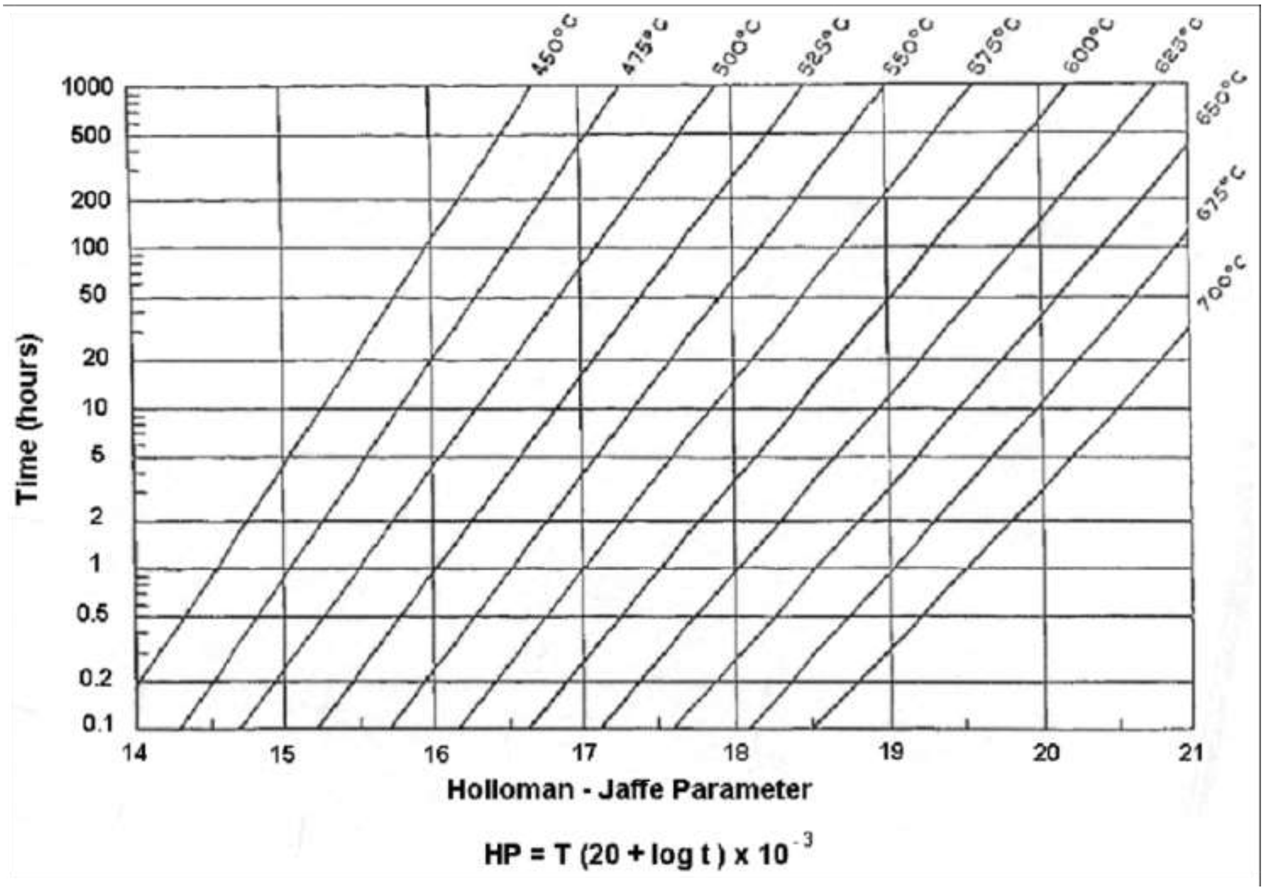
Original from https://steelselector.sij.si/steels/VCMO125.html. Estimated HP assuming 2 hr temper.

In the case Reynolds 725 the tubes are heated to 865C, soaked for 30 minutes, quenched in oil, then tempered to 570C for one hour resulting in a UTS of ~1200 MPa (Lynch and Jannetti, 2010). UTS (red) is greatly reduced and yield strength (blue, 0.2% proof stress) is little changed from the as quenched state, but ductility (green) and charpy impact resistance (not shown) are improved. Even so, UTS and yield strength are much improved compared to regular normalized and stress relieved 4130. One Reynolds document gives the following figures for UTS and YS. Admittedly this doesn't match up well with the temper chart above, which I assume uses a temper time of 2 hours on some unknown shape or size of 4130, but it remains illustrative of trends. Details of heat treatment may vary. The long soak times are generally not required for thin sections to austenitize, and austenitization should occur within normal brazing times.

REYNOLDS Steel Brands	853	631	725	525	953	931	921
Mechanical Properties							
UTS (min) (MPa)	1200	800	1050	750	1650	1100	1000
YS (min) (MPa)	1000	650	800	600	1450	1000	800
E% min	8	10	8	10	8	8	10
Poisson's Ratio	0.34	0.34	0.34	0.34	0.30	0.32	0.28

Reynolds technology (2013)

Factory temper usually involves a long soak at the target temperature, meaning that the tube can be reheated to up to the same temperature with little detrimental effect. As seen in the figure below, the state of temper is a function of temperature as shown by the lines, and time is on a log scale. Short exposure at a high temperature has a relatively high effect, but adding more time at same temperature has a lesser effect. If the steel has a Holloman – Jaffe parameter (HP) of ~16.9, due to being tempered at 570C for one hour, adding a few minutes of 570C heat increases the temper by very little. Generally speaking for subcritical temperatures, increasing time at temperature is bad, but increasing temperature is worse. Both should generally be kept as low as reasonably possible without creating other problems.



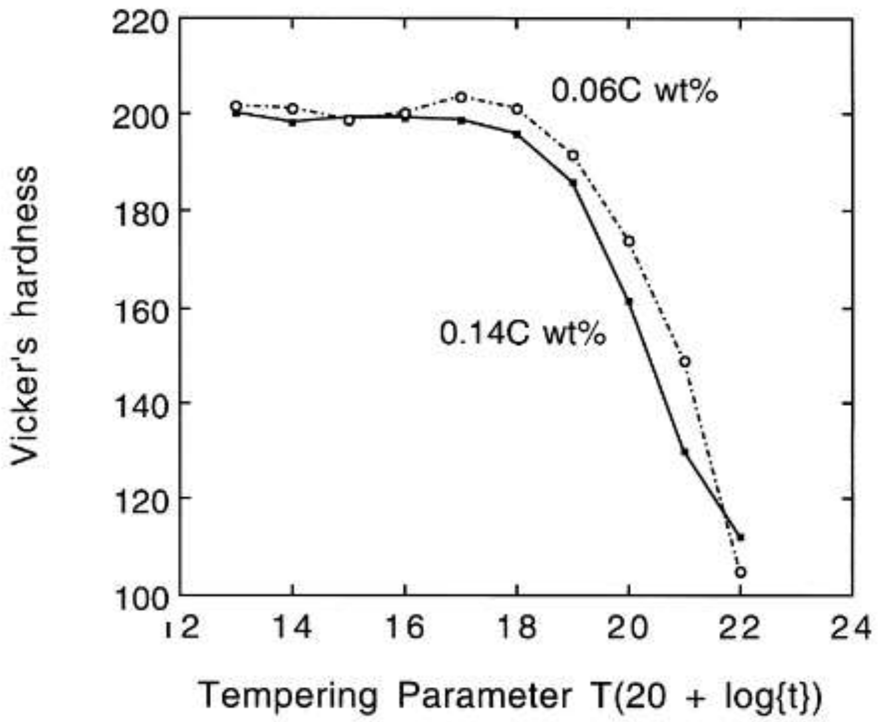
T in K, t in hours

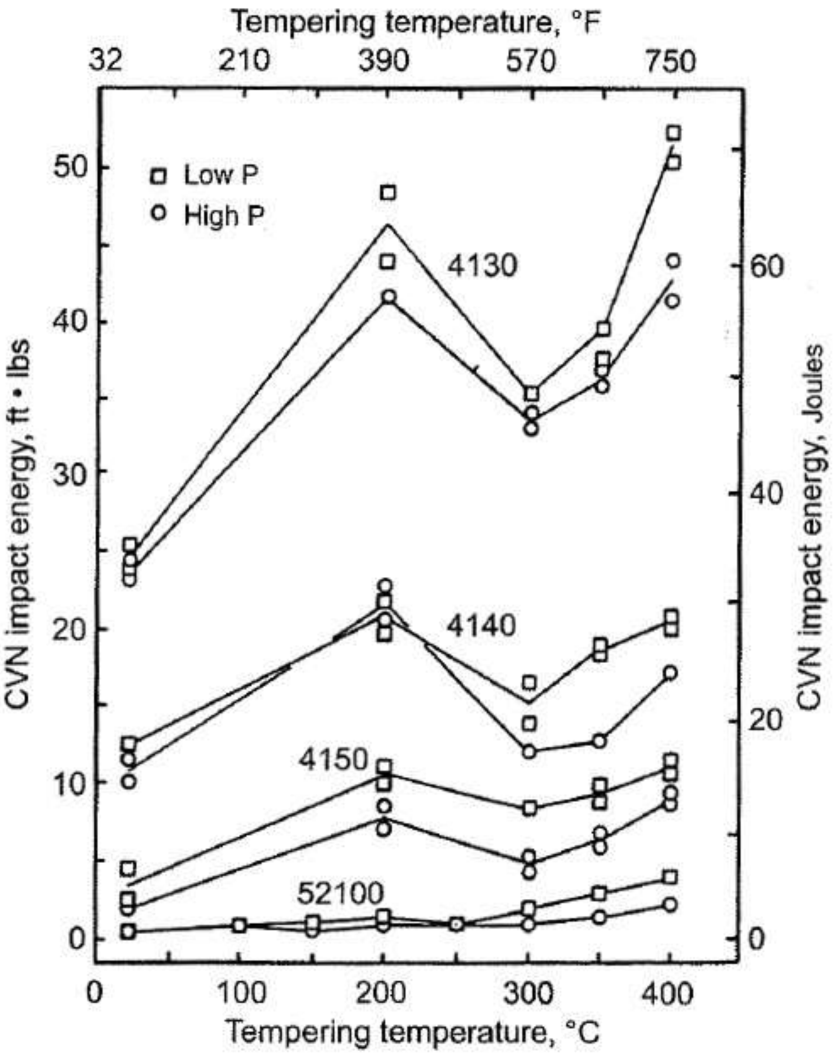
Assuming that the temper state HP for “heat-treated” 4130 is ~16.9, this state of temper is equivalent to ~1 minute at 650C, ~22 seconds at 675C, ~8 seconds at 700C, ~3 seconds at 725C, and ~1 second at 750C. Adding 10 minutes of time at silver temperature increases HP to ~17.8 (~615C at 1 hour). This is equivalent to only ~3 and a half minutes at 675C, ~1 minute at 700C, ~24 seconds at 725C, and ~9 seconds at 750C. Therefore it would appear that the technique of using a hot flame to heat the joint quickly to lower cycle times may be flawed for heat treated 4130, as spending a full 10 minutes trying to maintain the lowest brazing temperature possible is about as harmful accidentally overheating the steel to 750C for ~9 seconds. Additionally, this effect is not linear, attempting to halve the brazing time at 650C to 5 minutes only reduces HP to ~17.6 (~605C at 1 hour). Note that A1 is ~742C and partial austenization will start occurring at this temperature, so HP at 750C is only shown to show scaling. See below for the approximate color of steel at different temperatures.

For other steels, bainite tempering appears to start having an effect around HP ~18, or ~16 minutes of brazing at 650C, ~5 minutes at 675C, or ~2 minutes of brazing at 700C, however this may still prove to be a concern when a previously brass brazed joint with bainite is heated by additional brazing nearby. Given the steel is different, and the type of bainite is probably different, this is of limited use except to show that bainite does reduce in strength due to tempering, but the HP required to temper them it relatively high.

Tempering bainitic steel

Because a brass brazed joint appears to sometimes form some fraction of martensite when it cools, it may be tempting to attempt tempering at ~300C (dark blue oxides) where the above tempering chart indicates peak yield strength. However 4130 suffers from tempered martensite embrittlement. At that temperature small cementite carbides take on the form of plates along grain boundaries.



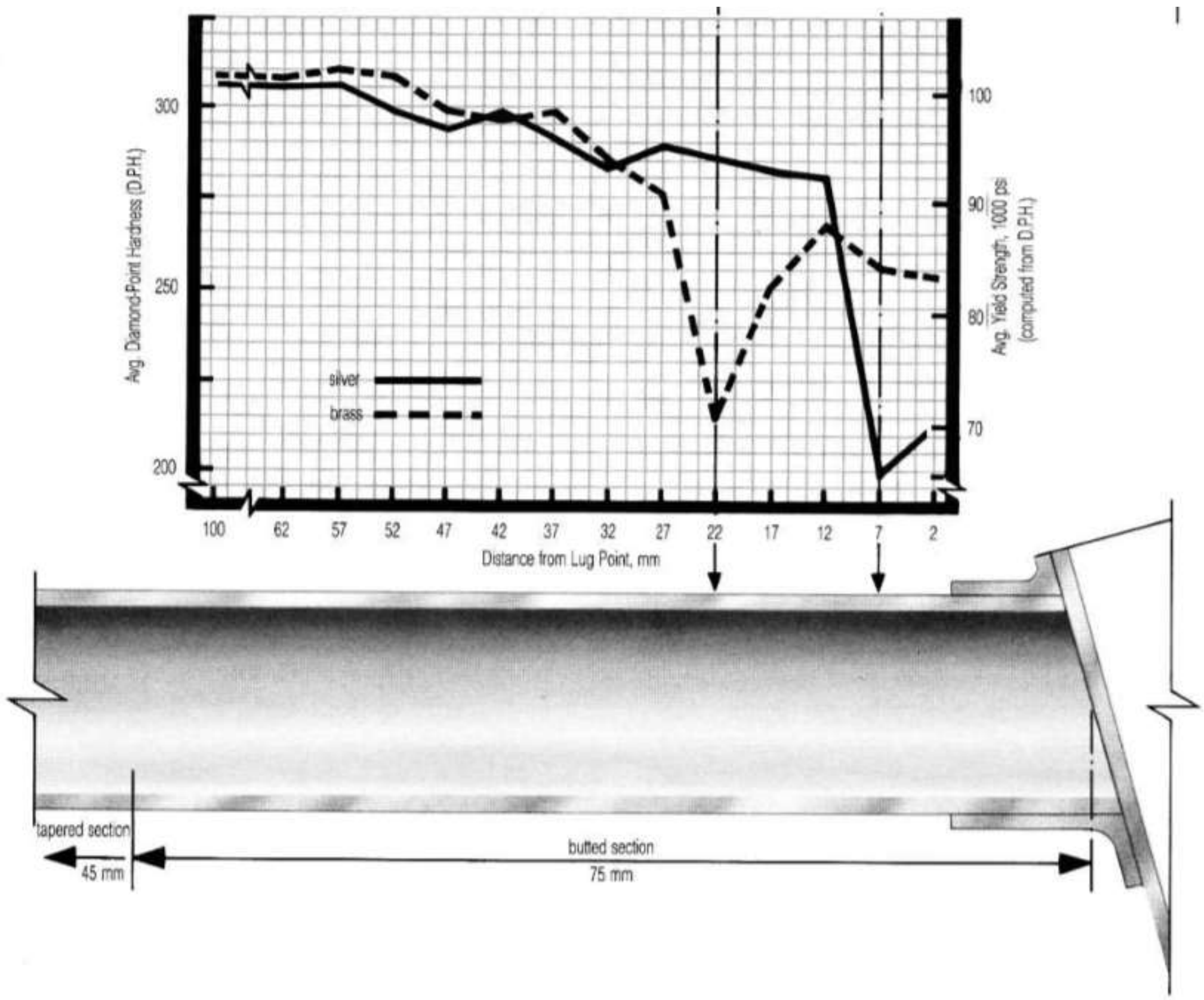


Brittle failure is the most dangerous kind of failure. Attempting to temper with a torch at ~200C (light yellow oxides) where there is a peak in toughness, little drop in UTS and a sizable increase in yield strength may be tempting, but there is a risk of overheating with poor torch control and it is unlikely you can achieve the appropriate soak times required.

When it comes to quenched and tempered "heat treated" steels, the temper is taken care of by the factory. When silver brazing such tubes, care must be taken to minimize temperature first, and time at heat second. However, the process of brass brazing or welding may form some martensitic or bainitic sections due to temperatures that exceed critical and the fast cooling rate of bicycle frames. Emiliani's (1983) experiments show that brass brazed joints may exhibit disappointing yield strength. It may be explained by martensite or residual stresses and tempering may result in improvement. It is possible that adding in an oven baking process at ~200C such as often used to dry frames after soaking in water to remove flux, or for power coating, or even ~100C used for baking some wet paints, may have a small but beneficial effect after brass brazing, and is well within frame builder norms.

Lugged construction

Further experiments were carried about by Emiliani (1983) on lugged joints of Reynolds 531 brazed by frame builder Richard Sachs. While not the same as 4130, it is in the same class of materials, and general trends can be assumed to apply to the construction of 4130 frames.



It is necessary to note that Emiliani (1983) took measurements every 5mm, and there can be large variations in strength over 5mm as shown by Columbus Tubi (1987). Therefore it is not possible to determine the degree or location of comparative minimum strength based off of Emiliani's (1983) testing. There are a couple trends that can be observed however. First, the weakest area is offset ~15mm further from the joint with brass. Second the brass tube recovers some strength either through normalizing or hardening, however the silver brazed tube is weakened right at the joint and near the stress riser caused by the lug.

Columbus Tubi (1987)

It may be noted that hardness, used as a proxy for yield strength, did not increase past the values for the tubing as delivered. One explanation is that yield strength doesn't track UTS well when crossing the through intercritical temperatures (between A1 and A3, ~742-826C) due to the changes in microstructure occurring there.

Figure 4a

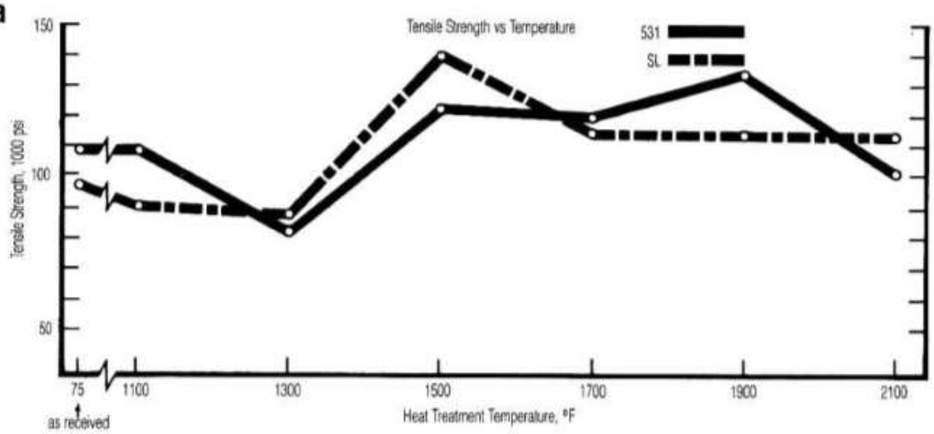
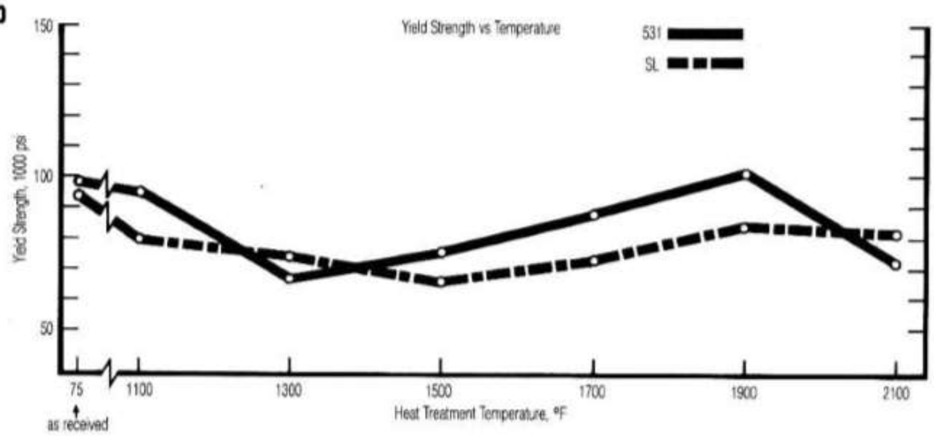


Figure 4b



Emiliani (1983)

Another possible explanation is the way the joint was heated, and the thermal mass of the lug slowing down the cooling rate. Brazing only one part of the joint at a time results in heat being added to adjacent areas. Below is a diagram of the heat a fillet brazed joint is speculated to experience by Bontrager (1985) but it may reflect the kind of heating a lugged joint may see with some brazing techniques. This can slow the rate of cooling from critical, resulting in different microstructure such as soft pearlite. It can also reheat the adjacent steel, tempering martensite or bainite that may have formed, or causing recrystallization. In some cases, this may not be an entirely bad thing. Tempering of any formed martensite may stress relieve and toughen the steel, but that is contingent on the formation of brittle untempered martensite. However, this is speculative, the expected low martensite fraction, bainite's relatively slow rate of tempering, and lack of cold working after brazing may mean tempering or reheating the rehardened areas may have little effect. Emiliani (1983) also shows this loss of strength when Columbus SL (25crmo4 at the time of the experiment) is heated to 1300F (704C) and 1100F (593C) for five minutes, showing that silver brazing temperatures produce comparatively weak tensile strength.

Note that the author explicitly states that the lines between data points can not be used to interpolate and it is likely that the chart does not show minimum nor maximum values. When comparing the yield strength however there is no increase at the brass brazing temperature 1700F (927C), however interpretation of this data is difficult and these samples may not have cooled in a realistic way. Subcritical annealing also occurs in this temperature range, which results in a very weak spheroidized microsctructure, however this process usually takes several hours, and is hopefully negligible for the time scales involved in brazing.

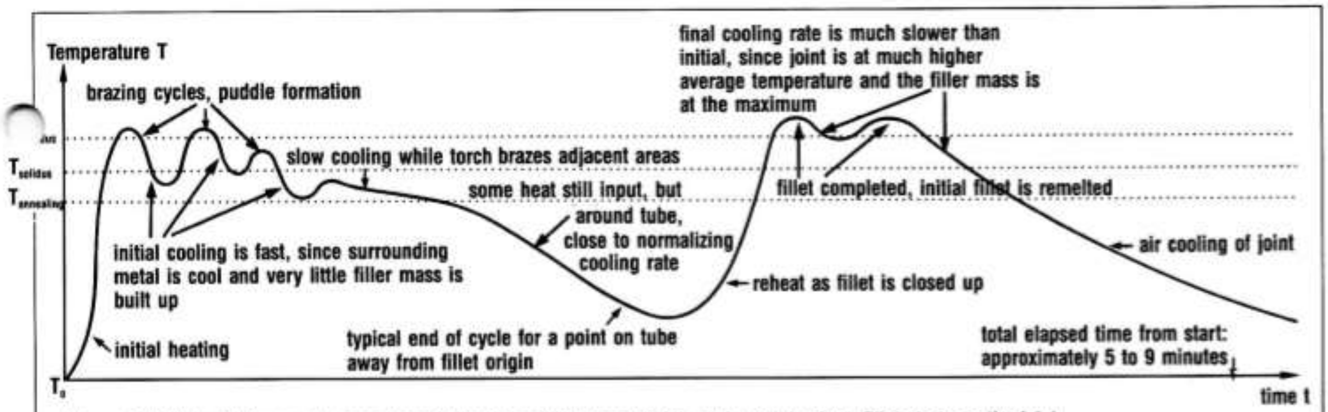


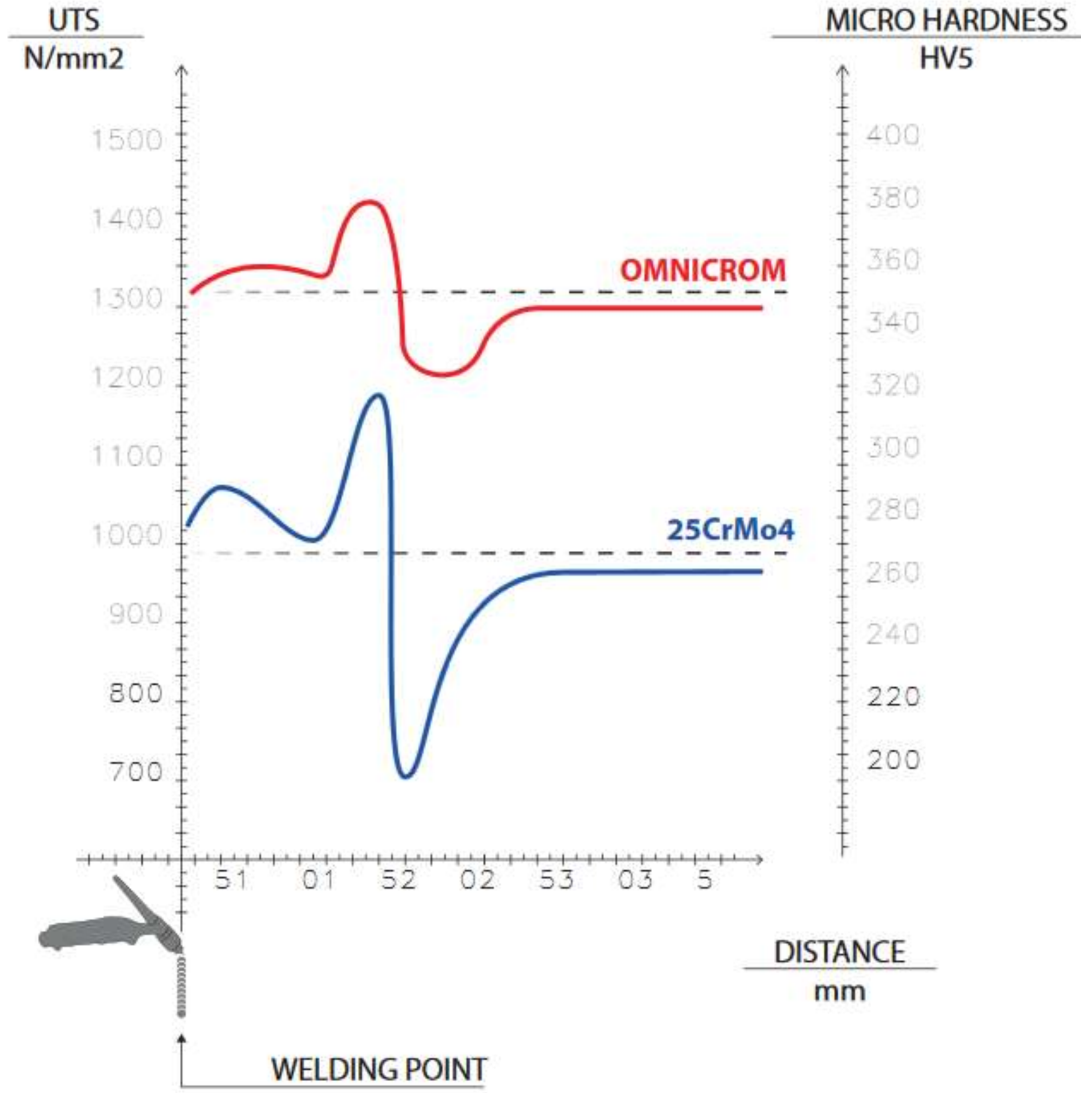
Figure 1: Anticipated time-vs.-temperature history for a fillet brazed joint, at the point where fillet starts on the joint.

Bontrager (1985)

While silver brazing distorts the frame less due to less extreme temperature differentials and is compatible with stainless fittings, silver brazed joints experience significant weakening of cold worked tubes directly at the joint, where stress risers are located and stresses are highest. As noted earlier, the strength losses associated with subcritical temperatures are functions of time and temperature, so both should be minimized as much as reasonably possible. Some frame builders note that distortion due to higher temperatures results in higher residual stresses, which may reduce fatigue life, however some methods with the same materials result in more distortion than others. The amount of benefit in the reduction of residual stress is unknown, but should generally be minimized. Reynolds has previously advised brass brazing 631/853, so I suspect the benefits of a stronger joint outweigh the cons of residual stress. Heat treated 4130 or precipitation hardening steels such as Columbus Omnicron (or Cyclex shown above, or various other Columbus precipitation hardening steels) may prove superior due to precipitation hardening (hardening when aged at temperature) countering the loss in strength from tempering or recrystallization.

A note about Cyclex. Some have claimed this is identical to 4130/25cromo4 that was being used by Columbus prior. I think it is pretty clear it is not. The graph would show much more similar characteristics between Cyclex and 25cromo4 between the hardened part and the point of lowest strength if this were true. Furthermore, Columbus has explicitly stated that Cyclex is a modification of 25cromo4, with elements added to facilitate precipitation hardening. It is not just a relabeling of 25cromo4. These kinds of steels are necessarily more expensive because they are neither the kind of industry standard steel stocked by a typical metal supply company, annealing is made more difficult, and tubes may need to be annealed multiple times during the drawing and butting process.

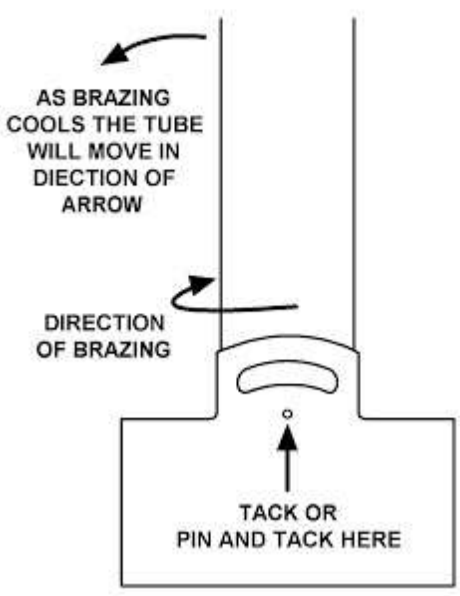
As a general rule, stress risers occur at braze-ons, lug points, the end of the seatpost clamp slit, joints and the tapered part of the tube butting Stress from braze-ons and lug points tend to be related to the changes in thickness caused by the additional material, meaning fillets and thinned lugs tend to produce fewer stress risers. The stresses along a bending butted tube will tend to be high at the miter, decrease until the end of the butt, then increase as the tube thins along the taper, then decrease along the length of the center. This means the high stress points are at the miter/lug and the thinner area of the tubing centered at the transition from taper to center.



Columbus Tubi (2018)

Brass brazing, unlike silver, hardens or at least normalizes and increases instrength relative to the tempered or recrystallized zone. This means that the steel at the miter/lug or braze on is higher strength than that of silver brazing for cold worked tubes. In effect, the weak area is pushed ~15mm from the point of brazing, as shown by Columbus (1987) and Emiliani (1983). While this means that the HAZ is somewhat increased, it can be manipulated away from stress risers, meaning the areas with lower fatigue/yield strength are in areas with lower stresses. In respect to joints, this means that optimally the weakened area should end up somewhere on the butt, which is shown by Emiliani (1983) to happen on a typical brass brazed lugged joint when the length of the buttextends 3-4cm past the point of the lug, but this is by no means a strict minimum.

One of the major issues with brass brazing is distortion due to the expansion of metal, especially resultant residual stresses and the need to align. Below is an illustration by frame builder Dave Moulton of the effects of distortion is practice. It also illustrated by Bontrager’s (1985) speculated temperature diagram for fillet brazing may still reflect the heat seen by a lugged joint brazed with a small oxy-acetalyne flame. As mentioned previously, such a construction technique may risk slowing cooling when the steel cools from brass brazing temperature or cause tempering.



Moulton (2008)

Hearth Brazing at Mercian Cycles

On the other hand traditional hearth brazing methods (brazing in a pile of strategically placed fire bricks) still employed by Mercian, Pashley and others result in less distortion as the joint is heated evenly with a large flame and reflected heat so all parts of the joint expand and contract relatively evenly. The drawback is that the HAZ tends to be larger than the samples brazed by Richard Sachs for Emiliani due to a larger area being heated and the area being heated for longer periods of time. This would appear to be less of an issue for the areas that reach brass brazing temperatures and reach critical temperature due to hardening or normalizing after, but growth of the tempered or recrystallized area is a concern. Use of heat sinks or heat sink pastes may help with growth of the tempered or recrystallized area, but run the risk of excessive hardening and increasing the martensite fraction due to an increased cooling rate, resulting in brittleness.

Brazing complex joints with multiple braze joints nearby present another conundrum. Although the braze joint will normalize or harden if brass brazed and increase in strength, areas around it, including other braze joints may be tempered or recrytallized and weakened. This can be dealt with by brazing all nearby joints in one operation, such as was done in mass production bottom brackets, or strategic brazing order to maximize the strength of areas most prone to failure. Similar consideration should be given to braze-ons. Using heat sinks or paste heat sinks may have some benefit in preventing the back tempering of steel when brazing adjacent to a stress riser that is already brazed on.

In regards to “heat-treated” (quenched and tempered) 4130, silver should be used at the lowest possible temperature, and then heating for no longer than needed. Accidental overheating can cause as much tempering in mere seconds as minimum brazing temperature does in several minutes. Brass brazing will likely end up no worse on “heat-treated” tubes compared to equivalent cold-drawn ones, but “heat-treated” 4130 is often drawn thinner. Austempered bainitic 4130 would probably make a good tube for silver brazing.

Fillet Brazing

Fillets have traditionally made with a radius ~4 times the wall thickness of the tube. However Bontrager (1985) notes that smaller fillets preserve more of the tubes strength. Small fillets have traditionally been dismissed (Paterek) but large fillets introduce their own problems.A fillet is an external casting and subject to casting imperfections and cracks (Kay, 2010). Further small fillets should be sufficient in strength as brazing will usually fail in the base material and joint strength can exceed the strength of the raw filler material as long as gap size is kept small (Kay, 2019).

Table 1: Test specimen identification and average measured hardness (Rockwell B).

Sample Number	Material	Joining Time (min)	Fillet Radius (inches)	Average measured hardness (Rockwell B) at specified distance (inches) from fillet edge (see Fig. 4) .0	.1	.2	.3	.4	.5	.6
1	I	9	.75	85.5	83.3	94.5	99	100	—	—
2	R	9	.50	86	89	90	96	98	—	—
3	I	5	.37	90	95	93	99	99	—	
4	R	6	.28	89	89.5	89	96	97	97	—
5	R&I	6	.21	96	95	95.5	94	95	98	—
6	I	6	.15	93.5	91	97	99	100	100	—
7	R	5	.10	97	95	92	97.5	100	100.5	100
8	R	3	TIG	100	97	97	98	97	—	—
9	I	3	TIG	101	99	98	100	100	100	100
10	R	tube "as delivered"		99	(control sample, not brazed)					
11	I	tube "as delivered"		98.5	(control sample, not brazed)					
12	R	TIG weld bead (Fig. 5)		see Table 2 for data						

I = Ishiwata "CrMo," R = Reynolds 531

	As-delivered Condition	Heat-Affected-Zone	Brazed Area	Weaknesses	UTS at joint or stress risers
Cold-drawn brass brazed	~800 MPa, work hardened	Falls to ~650-700 MPa, similar to normalized due to recrystallizing	Possibly increased strength vs HAZ, varies with rate of cooling and tempering	Weakest in HAZ, away from joints and stress risers, more residual stress	~750-1200 MPa
Cold-drawn silver brazed	~800 MPa, work hardened	Falls from as-delivered to brazed condition due to recrystallizing	~650-700 MPa, similar to normalized due to recrystalizing	Weakest near joints and stress risers	~650-700 MPa
Heat-treated brass brazed	~1200 MPa, tempered martensite	Falls significantly more than silver due to over tempering	Possibly increased strength vs HAZ, varies with rate of cooling and tempering	Weaker in HAZ than silver, more residual stress	~750-1200 MPa
Heat-treated silver brazed	~1200 MPa, tempered martensite	Falls from as-delivered to brazed condition due to tempering	~950-1100 MPa, tempered martensite, varies with temperature and time	Weakest near joints, but joints still very strong	~950-1100 MPa

Expected typical behaviors brazing 4130

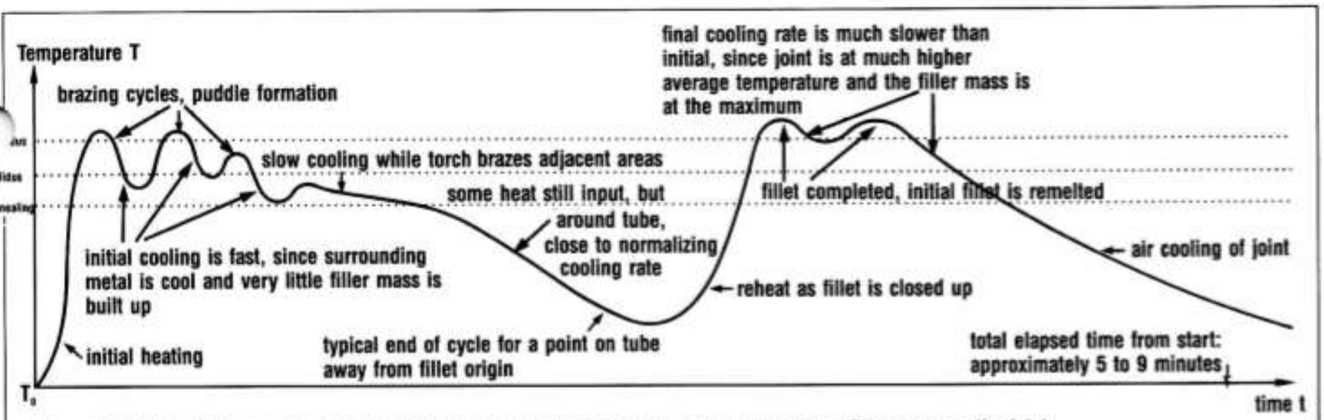
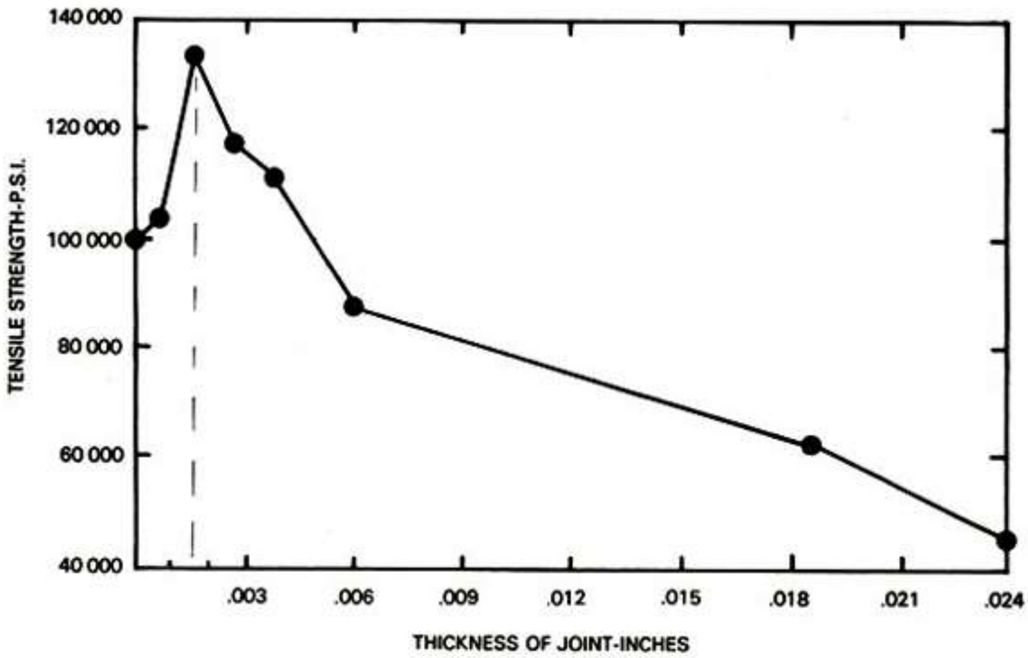


Figure 1: Anticipated time-vs.-temperature history for a fillet brazed joint, at the point where fillet starts on the joint.



Bontrager (1985)

The effect of reducing stress risers is also largely not necessary. Welded frames hold up fine with very small fillets. Main tubes are loaded primarily in compression and tension, not bending (Allen, 1982).Large fillets do have some advantages, the most significant probably being aesthetics. Large fillets likely do help distribute stresses, even if it is unnecessary. In the case of poor miters, large fillets probably add strength to the joint by acting as a non-penetrating bronze weld.

The heating pattern described by Bontrager (1985) and the negative effects mentioned previously are still of concern. Internal fillet brazing as described by Patarek, employed by builders such as Jo Routens, and found on mass produced frames such as Peugeots and the top tube/seat tube joint of Schwinn Varsities could be employed. It would also reduce distortion.

Welding

Options involved in altering welding techniques are limited. Some builders use heat sinks to reduce distortion and HAZ. While it may help, the benefits of reduced HAZ are questionable. HAZ is already very small with welding, but due to the extreme temperatures and rapid cooling, there are more zones within a weld HAZ. 4130 is typically preheated to prevent martensite formation near the weld to prevent brittleness (or stress releived after welding). Heat sinks would only make this worse. However selection of appropriate filler materials can reduce the chance of martensite formation. Grain growth from the high temperatures may still be a problem.