Balancing High Strength Tubing Selection and Cost in Hydraulic System Design

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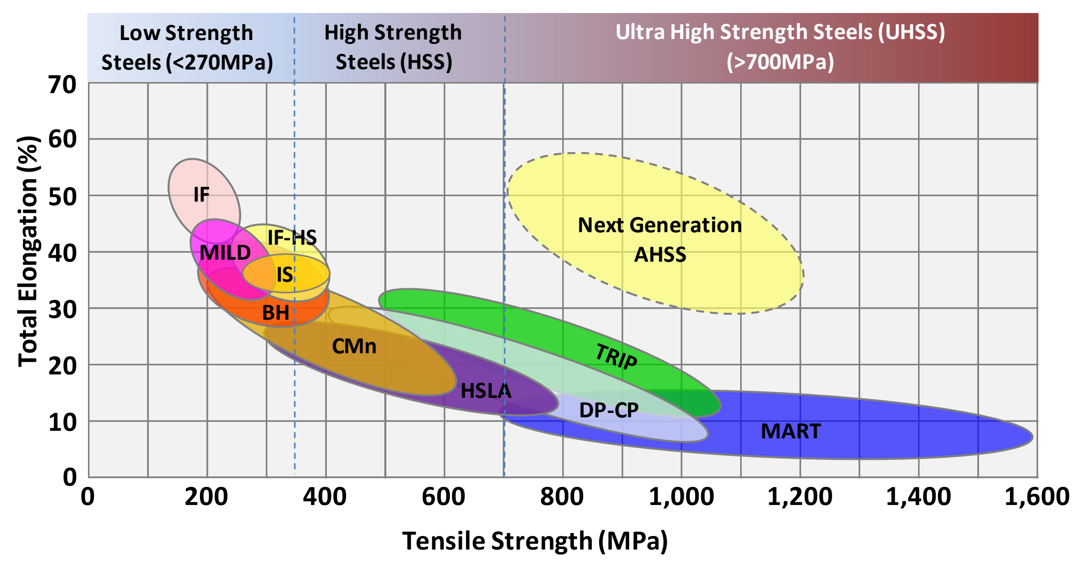
ABSTRACT

The automotive industry has fueled many advances in high strength steel materials as we know them today. Vehicle body panels and structural components have benefited significantly from decades of development targeted at improving vehicle occupant safety and reducing overall vehicle weight for enhanced fuel economy. At the same time, ferrous and non-ferrous tubing options for hydraulic system design have changed little. While this has served to simplify and standardize design practices, the trend toward higher hydraulic system pressures and improved system efficiency has created difficulties for the designer in material selection. Hydraulic system engineers seeking ferrous or non-ferrous tubing options capable of meeting the demands of today's higher pressure systems are often faced with limited choices and very real cost constraints. This writing will present a brief history of high strength steel development, explore current high-strength tubing options and their impact on system design, and investigate new developments in high strength hydraulic tubing that give the designer more cost-effective alternatives to meet overall system design objectives.

High Strength Steel Development

Since the 1960's the automotive industry has been one of the primary drivers in the development of high strength steels as the need arose to improve vehicle fuel economy and increase occupant safety. Initial efforts began with development of now familiar High Strength Low Alloy (HSLA) steels and accelerated in the 1990's through the efforts of the Ultra-Light Steel Auto Body (ULSAB) consortium. Collaborative work done under the umbrella of ULSAB led to more exotic specialized steels specifically tailored to automotive industry needs. The chart in *Figure 1* below is often referred to as the classic "banana chart" and plots the relative tensile strength in megapascals (MPa) and elongation for various categories and grades of steels. It also visually demonstrates the typical inverse relationship between tensile strength and ductility. The left-most region of the chart in *Figure 1* includes Low Strength Steels (LSS, < 270 MPa tensile strength) which are generally made up of low carbon mild steels, bake hardened steels, interstitial free steels, and other similar grades. LSS have exceptional ductility, as indicated by their high observed elongation values, and lend themselves well to forming and bending. The middle region of the chart includes various High

Figure 1 *- Relative Tensile Strength and Elongation for LS, HSS, and UHSS grade steels, Source: worldautosteel.org* [1]



Strength Steel (HSS) grades having tensile strengths between 270MPa and 700MPa. HSS include Carbon Manganese (CMn) and various High Strength Low Alloy (HSLA) grades that achieve higher tensile strengths either with additional C and Mn content, the addition of various micro-alloying elements, and/or manufacturing techniques that promote grain refinement and target specific microstructures. In general, HSS grades are less ductile than LSS grades. Finally, the right-most region of the chart includes Ultra High Strength steels (UHSS, > 700Mpa tensile strength). UHSS are some of the strongest steels currently available with tensile strengths reaching to 1,600MPa and beyond. UHSS typically exhibit the lowest ductility of any of the grades discussed in this writing.

Modern vehicle chassis designers have made good use of many grades and classes of steels as illustrated in *Figure 2* below. Materials are selected for their unique properties to achieve overall design objectives for strength, cost minimization, impact resistance, and energy absorption. The end result is a vehicle with less mass leading to improved fuel efficiency yet enhanced safety for occupants. Current research is focused on next generation structural steels having additional ductility and strength, thus shifting the curve both up and to the right.

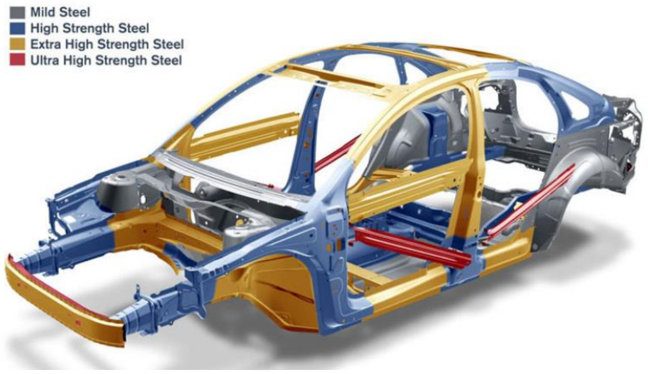


Figure 2 *- Typical Structural Steel application in passenger vehicle chassis design, Source: worldautosteel.org* [1]

Hydraulic Tubing Development

While advancements in steel chemistry and processing techniques have significantly improved the mechanical properties of structural steels, relatively few of those advancements have impacted the hydraulic tubing market. This is potentially due to several factors:

- The hydraulic tubing industry requires tubing with significant ductility that can be easily cold worked. The severity of cold work induced ranges from simple bends and flares to more complex forms and shapes often found in tube end fittings.

- Adding carbon to increase strength quickly reaches a point of diminishing returns as ductility is degraded.

- The majority of hydraulic tubing used today is Draw-Over-Mandrel (DOM) tubing. High strength structural steels are often manufactured with specialized hot rolling processes that give them their added strength and ductility in the as-rolled state. Steels produced by such processes do not lend themselves well to the cold work and subsequent annealing required in the production of DOM hydraulic tubing.

There are four key SAE standards that cover the majority of hydraulic tubing manufactured and consumed in the United States. The first of these, SAE J525, was published in 1958 and outlines chemistry, mechanical, and other requirements for what has been a staple of the hydraulic tubing industry.

Slow developments and improvements in hydraulic tubing can clearly be seen in the timespan that elapsed between the introduction of SAE J525 and the introduction of the next hydraulic tubing standard, SAE J2467, which was not published until 1999. Additionally, the only significant change in J2467 was an increase in the carbon (C) and manganese (Mn) content of the steel. A comparison of all four SAE hydraulic standards is provided in the *Table 1*.

		SAE J-525	**SAE J-2467**	**SAE J-2614**	**SAE J-2833**
	Comparison of SAE Hydraulic Standards	ERW, Cold Drawn, Low-Carbon, Annealed for Bending and Flaring	ERW, Cold-Drawn, SAE 1021, SAN for Bending and Flaring	ERW, Cold-Drawn HSLA, Sub-Critical Anneal for Bending and Flaring	ERW, Cold-Drawn HSLA, SRA for Bending and Flaring
	Year Published	*1958*	*1999*	*2003*	*2009*
Chemistry	Carbon (C)	0.06 min/0.18 max	0.17min/0.23 max	0.18 max	0.26 max
	Manganese (Mn)	0.30 through 0.60	0.60 through 0.90	1.50 max	1.60 max
	Phosphorus (P)	0.04 max	0.04 max	0.035 max	0.035 max
	Sulfur (S)	0.05 max	0.05 max	0.035 max	0.035 max
	Silicon (Si)	n/a	n/a	0.35 max	0.35 max
	Aluminum (Al)	n/a	n/a	0.020 min	.020 min
	Micro Alloying Elements	n/a	n/a	0.15 max	0.15 max
Mechanical	Mpa Yield Strength (min)	170	275	345	620
	Mpa Tensile Strength (min)	310	415	500	690
	Elongation in 50mm (min)	35%	25%	30%	15%
	Hardness (max)	Rockwell B65	Rockwell B75	Rockwell B90	Rockwell B100
	Hardness (target)	None stated	None stated	Rockwell B85	Rockwell B92

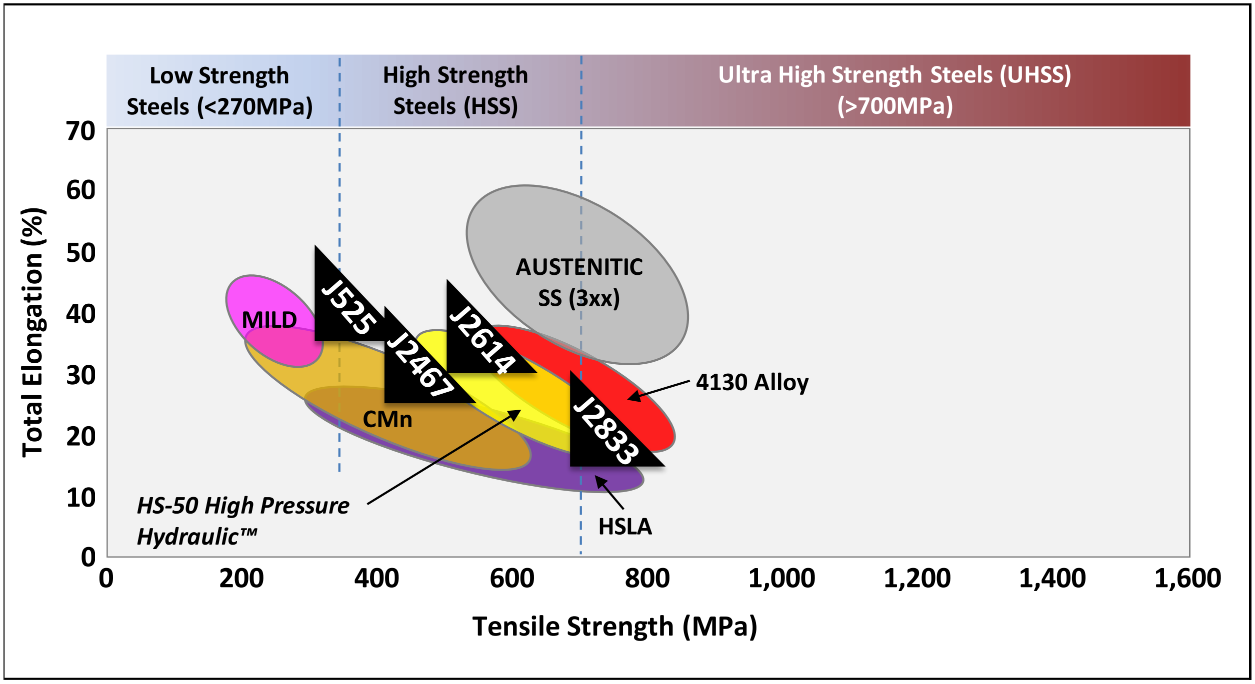
Table 1 *- Comparison of SAE Hydraulic Tubing Standards*

To categorize the four SAE hydraulic tubing standards in the context of the classic "banana" chart from *Figure 1*, SAE J525 hydraulic tubing is generally manufactured from C1010 grade low-carbon (mild) steel. SAE J2467 is a higher strength hydraulic tubing alternative that fits neatly into the CMn steel grade(s) with its increased carbon and manganese content over steels specified by SAE J525. C1021 grade steel is required to meet the requirements of the SAE J2467 standard. SAE J2614 is an even higher strength alternative that calls for a micro-alloyed steel and would represent the more ductile range of the HSLA grade region represented in *Figure 1*. Hydraulic tubing made to meet the SAE J2614 standard will require steels alloyed with one or more of the following to achieve the desired mechanical properties: Columbium (Cb), Niobium (Nb), Vanadium (V), Titanium (Ti) or other micro-alloying elements. Finally, SAE J2833 is the highest strength of the four hydraulic tubing alternatives and also calls for micro-alloyed steels that would generally fit into the less ductile range of the HSLA grade region represented in *Figure 1*. Commercially, hydraulic tubing meeting the SAE J2833 standard is available in the market, but SAE J2614 hydraulic tubing is scarce at best.

There are other high-strength alternatives available to the hydraulic system designer. Seamless 4130 grade steels are commonly used in aircraft and other critical or specialized hydraulic applications. Stainless steels are some of the most ductile available with very high tensile strengths compared to most standard hydraulic tubing alternatives. Stainless steels also have the added benefit of excellent corrosion resistance when required by the application. Both 4130 and stainless steels have their own unique place in the structural steel and hydraulic tubing market; however, the benefits they offer in the areas of strength, ductility, and other unique properties, like corrosion resistance, are often offset by significantly higher costs. Unless their specific mechanical or physical properties are needed, hydraulic system designers will often select a lower-cost alternative.

The chart in *Figure 3* is similar to the chart in *Figure 1* and shows the relationship of various steel grades to specific SAE hydraulic tubing specifications discussed above. Some grade regions have been eliminated for clarity while 4130 and Austenitic Stainless steels have been added to show their relationship. A region representing Plymouth Tube's new ***HS-50 & HS-90 High Pressure Hydraulic Tubing™*** has also been added and will be discussed in more detail later. Note that HS-50™ meets the chemistry and mechanical requirements of SAE J2614 while HS-90™ meets the requirements of SAE J2833.

Figure 3 *- Typical Hydraulic Grade Steels and applicable SAE Standards*



Hydraulic System Design Using High Strength Steels

Hydraulic system design is a straightforward science. System designers use standard calculation methods and select materials that achieve the most efficient and cost effective balance among the following criteria:

- Meet system design pressure minimums
- Minimize pressure drop
- Minimize heat generation
- Reduce fluid turbulence
- Eliminate cavitation on suction lines
- Minimize system cost
- Maximize overall system efficiency

While this text is not intended to be a source for hydraulic system design, reviewing the process will help show the importance of new, higher-strength tubing developments and how they benefit the designer.

Table 2 *- Recommended Flow Diameter*[2]

Maximum flow rate, gpm	**Recommended flow diameter, in.**		
	Pressure Lines	**Return Lines**	**Suction Lines**
5.00	0.286	0.452	0.716
5.50	0.300	0.474	0.750
6.00	0.314	0.495	0.784
6.50	0.326	0.515	0.816
7.00	0.339	0.534	0.847
7.50	0.351	0.553	0.876
8.00	0.362	0.571	0.905
8.50	0.373	0.589	0.933
9.00	0.384	0.606	0.960
9.50	0.395	0.623	0.986
10.00	0.405	0.639	1.012
11.00	0.425	0.670	1.061
12.00	0.433	0.700	1.109
13.00	0.462	0.728	1.154
14.00	0.479	0.756	1.197
15.00	0.496	0.782	1.239
16.00	0.512	0.808	1.280
17.00	0.528	0.833	1.319
18.00	0.543	0.857	1.368
19.00	0.558	0.880	1.395
20.00	0.572	0.903	1.431
22.00	0.600	0.947	1.501
24.00	0.627	0.990	1.568
26.00	0.653	1.030	1.632
28.00	0.677	1.069	1.693
30.00	0.701	1.143	1.753

Step 1: Determine Required Flow Diameter

Table 2 (above) gives a few examples of Recommended Flow Diameters for required flow rates based on the following recommended flow velocities:

Pressure Lines – 25 ft/sec (7.62m/sec)
Return Lines – 10 ft/sec (3.05m/sec)
Suction Lines – 4 ft/sec (1.22m/sec)

For design velocities that differ from those given in standard tables, the designer can calculate the appropriate tube Inside Diameter (ID) using one of the following formulas based on the units desired.

To calculate Tube ID (*d*) in inches:

$$d = 0.64\sqrt{\frac{Flow\ in\ GPM}{Velocity\ in\ ft/sec}}$$

To calculate Tube I.D. (*d*) in millimeters:

$$d = 4.61\sqrt{\frac{Flow\ in\ lpm}{Velocity\ in\ m/sec}}$$

Step 2: Determine Tube OD and Wall

Pressure rating tables are available that allow the designer to quickly determine the tube diameter and wall thickness combination that satisfies system operating pressure and flow requirements. Design pressures for selected wall diameters for 0.500” Outer Diameter (OD) tubing are provided in *Table 3* for later discussion. If severity of service ratings other than “A” (normal) are utilized apply the appropriate derating factor to the values prior to selecting OD and Wall. Other known considerations for the system designer include temperature derating factors and tube D/T ratio in bending applications (again, the specific details of various service and temperature derating, etc. are not covered in this text, but readily available and known to the system designer).

Designers may also apply Lame's equation to determine appropriate OD and Wall thickness values required to meet system design pressure requirements.

Lame's equation follows:

$$P = S\left(\frac{D^2 - d^2}{D^2 + d^2}\right)$$

Where:

D = Tube OD (in)
d = Tube ID (in), or D-2T
P = Recommended design pressure (psi)
S = Allowable stress for design factor of 4, (psi)
T = Tube wall thickness (in)

For thin walled tubes (D/T ≥ 10) the designer can substitute Barlow's formula: ***P = 2ST/D***

Table 3 **-** *Design Burst Pressure*[2]

Tube OD, in.	**Wall thickness, in.**	**Tube ID, in.**	**Design pressure, psi (4:1 design factor)**			
			Steel 1010 (SAE J524 and J525)	**Steel 1021 (SAE J2467)**	**Stainless Steel (304, 316) 4130, HSLA,*Plymouth HS-50 Hydraulic***	**Copper**
0.500	0.049	0.402	2,700	3,250	4,050	1,300
0.500	0.058	0.384	3,250	3,900	***4,850***	1,550
0.500	0.065	0.370	3,650	4,400	5,500	1,750
0.500	0.072	0.356	4,100	4,900	6,150	1,950
0.500	0.083	0.334	***4,800***	5,750	7,200	2,300
0.500	0.095	0.310	5,550	6,650	8,350	2,650
0.500	0.109	0.282	6,450	7,750	9,750	3,100
0.500	0.120	0.260	***7,200***	8,650	10,800	3,450

Design Stress Values

The key variable in selecting tubing that satisfies system pressure requirements is the allowable design stress of the tube material itself. For general applications not requiring special corrosion resistance or high strength, C1010 steel has been the industry standard for decades.

A highly formable and bendable steel tubing, C1010 offers flexibility in meeting low-pressure design needs for fabricated port-to-port hard lines and hose end fittings at a minimal cost. *Table 4* (shown on Page 8) gives a side-by-side comparison of Allowable Design Stress Ratings for various material types.
From *Table 4* the designer can clearly see that HSLA steels, which include HS-50 High Pressure Hydraulic™, 304 and 316 Stainless Steel, and 4130 all offer a significant advantage in allowable design

stress over standard C-1010 steel. At a design factor of 4, this advantage amounts to a 50% increase in allowable design stress. To illustrate some of the potential benefits to the designer we turn to the following example.

Example 1

Our designer is looking at a hydraulic pressure line application that might normally use 0.500" OD x 0.083" Wall C1010 tubing at a design pressure of 4,800 psi (*Table 3*) and a flow of approximately 7 gpm (*Table 2*). In this case however, the system must operate at a target design pressure of 7,200 psi. Looking at *Table 3*, our designer sees that he has at least two options:

1) Increase the wall thickness of the tube to 0.120".
2) Use a higher strength material, like HS-50 High Pressure Hydraulic, with the original 0.500" x 0.083" tube dimensions.

The first option meets the design pressure constraint but requires such a heavy wall that the ID is reduced to only 0.260". This restricts flow volume to only 4.0 gpm (a 40% decrease) and could lead to other problems:

- Increased flow turbulence
- Increased pressure drop
- Increased heat generation
- Increased system weight (a 32% increase)
- Difficulty bending and forming
- Potential routing issues due to necessity of increasing minimum bend radii
- Cost impact of purchasing new tooling for bending/forming applications, etc.

The second option, substituting HS-50 High Pressure Hydraulic**,** also meets the design pressure constraint, but without the negative impact on flow diameter and other factors. The one impact that must be considered is whether the price premium of the higher strength material offsets these negative impacts.

Example 2

Our designer is looking at a similar hydraulic pressure line application that might normally use a 0.500" OD x 0.083" Wall C1010 tube. In this example the required design pressure is 4,800 psi and the designer wishes to improve flow to a minimum of 8.5 gpm.

Looking at *Table 3*, our designer sees that the 0.500" x 0.083" C1010 tube meets the 4,800 psi design pressure requirement with a tube ID of 0.334". This tube ID corresponds to a flow of approximately 7 gpm (*Table 2*). Looking again to *Table 3*, our designer also sees that he can reduce the tube wall to 0.058" by selecting HS-50 High Pressure Hydraulic. This choice increases the tube ID to 0.384" with a flow volume of 9 gpm, thus meeting the flow requirement for this application (a 28% increase in flow).

Negative impacts for this solution include slightly increased system cost and potential tooling costs. These costs should be weighed against multiple positive impacts:

- Improved flow (28% increase)
- Reduced pressure drop
- Reduced heat generation

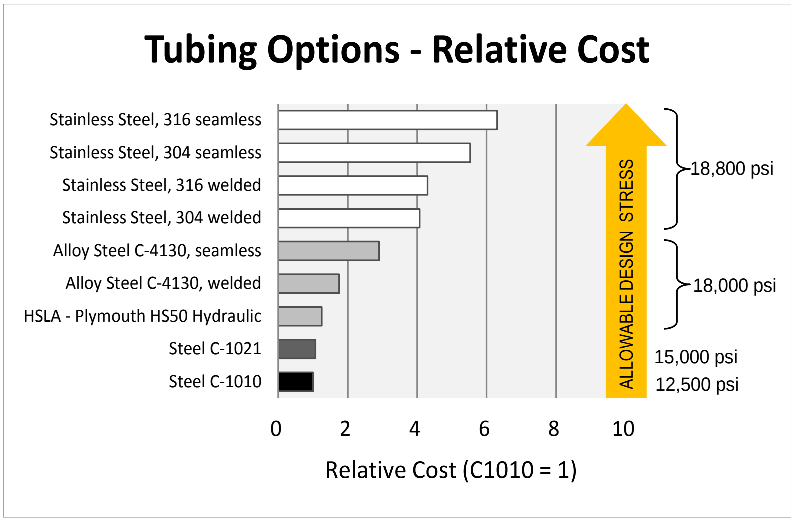
- Reduced system weight (26% reduction)

Table 4 *- Design Stress Rating*[2]

Material and Type	Allowable design stress, psi (Design factor of 4 at 72°F)	Tube Specification
Steel C-1010	12,500	SAE J356, J524, J525
Steel C-1021	15,000	SAE J2435, J2467
Steel, HSLA ***Plymouth HS-50 Hydraulic***	18,000	SAE J2613, J2614
Stainless Steel, 304 & 316	18,800	ASTM A213, A249, A269
Alloy Steel C-4130	18,000	ASTM A519
Copper, K or Y	6,000	SAE J528, ASTM B75

Cost Considerations

For the hydraulic system designer faced with new challenges, cost can often be the deciding factor that limits design flexibility. Higher strength hydraulic tubing alternatives have traditionally commanded a premium price. When compared to standard C1010 J525 Tubing, that premium can be as much as six times higher (chart below). Granted, the higher end of that scale is reserved for materials that have other special characteristics that make them necessary in applications where high corrosion resistance is needed, but even existing higher strength carbon steel alternatives can be two to three times the cost of C1010 J525.



HS-50 High Pressure Hydraulic Tubing offers the hydraulic system designer a cost-effective, high strength alternative to C1010 J525 that matches the allowable design stress rating of 4130 (and is very close to that of 304 and 316 stainless) at less than half the cost for like-sized tubing. In addition, designers will find that they are able to utilize the higher strength of HS-50 High Pressure Hydraulic to specify thinner walled tubing in standard applications allowing them to achieve higher flow rates and lighter system weights with little or no cost premium. Looking back at an earlier example (*Example 2*), our designer could switch from 0.500" x 0.083" C1010 SAE J525 to 0.500" x 0.058" HS-50 High

Pressure Hydraulic for less than a 5% increase in tubing cost, and have the added benefit of more flow and less system weight.

Conclusion

HS-50 High Pressure Hydraulic was developed to meet specific and emerging needs of the hydraulic tubing market at an attractive price. HS-50 High Pressure Hydraulic Tubing meets all chemical and mechanical requirements of SAE J2614 and has been proven to provide cold forming and bending characteristics similar to C-1010 SAE J525 tubing in various applications. Not only does HS-50 High Pressure Hydraulic Tubing offer the system designer expanded alternatives for design that help maximize system efficiency, there may be additional benefits in:

- Elimination of machined components for applications where existing tubing strength limitations create design problems.
- The ability to stock a single grade hydraulic tube that can meet both low pressure and high pressure system requirements, thus reducing inventory carrying costs and floor space requirements.

HS-50 High Pressure Hydraulic Tubing is offered in wall thicknesses of 0.035" to 0.120" and in outer diameters of 0.375" to 1.75" depending on OD-to-Wall ratio. Chemistry and mechanical requirements are given below. HS-50 High Pressure Hydraulic is also available as a stress relieved product, HS-90 High Pressure Hydraulic. HS-90 is suitable for bending and flaring for hydraulic lines and meets the requirements of SAE J2833.

CHEMICAL COMPOSITION	C% max	Mn% max	S% max	P% max	Si% max	Al% max	Micro Alloying elements (Ng, Cb, Ti, V) max
HS-50 High Pressure Hydraulic	0.18	1.5	0.035	0.035	0.35	0.02	0.15

MECHANICAL REQUIREMENTS	Yield Strength		Tensile Strength		Elongation	Applicable Specification
	MPa min	psi min	MPa min	psi min	% min	
HS-50 High Pressure Hydraulic	345	50,025	500	72,500	30	SAE J2614
HS-90 High Pressure Hydraulic	620	89,900	690	100,050	15	SAE J2833

References

[1] www.worldautosteel.org

[2] B. Bailey, Parker Tech Connect, *Sizing Tube to Maximize System Efficiency* (2013), pp 1-3.

[3] SAE Standards:

SAE J356 Welded Flash-Controlled Low-Carbon Steel Tubing Normalized for Bending, Double Flaring, and Beading
SAE J524 Seamless Low-Carbon Steel Tubing Annealed for Bending and Flaring
SAE J525 Welded and Cold Drawn Low-Carbon Steel Tubing Annealed for Bending and Flaring
SAE J2435 Welded Flash Controlled, SAE 1021 Carbon Steel Tubing, Normalized for Bending, Double Flaring, and Beading
SAE J2467 Welded and Cold-Drawn, SAE 1021 Carbon Steel Tubing Normalized for Bending and Flaring
SAE J2613 Welded Flash Controlled, High Strength Low Alloy Steel Hydraulic Tubing, Sub-Critically Annealed for Bending, Double Flaring, and Bending
SAE J2614 Welded and Cold-Drawn, High Strength (500 MPa Tensile Strength) Low Alloy Steel Hydraulic Tubing, Sub-Critically Annealed for Bending and Flaring
SAE J2833 Welded and Cold-Drawn, High Strength (690 MPa Tensile Strength) Low Alloy Steel Hydraulic Tubing, Stress Relieved Annealed for Bending and Flaring
SAE J528 Seamless Copper Tube

[4] ASTM Standards:

A213 Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes
A249 Standard Specification for Welded Austenitic Steel Boiler, Superheater, Heat-Exchanger, and Condenser Tubes
A269 Standard Specification for Seamless and Welded Austenitic Stainless Steel Tubing for General Service
A519 Standard Specification for Seamless Carbon and Alloy Steel Mechanical Tubing
B75 Standard Specification for Seamless Copper Tube