PRECISION STEEL TUBE HANDBOOK

**– COMPILATION OF TRAINING MATERIAL
FOR BENDING, WELDING AND COATING**

SSAB

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Contents

"Does it contain any abstract reasoning concerning quantity or number?

No. Does it contain any experimental reasoning concerning matter of fact and existence?

No. Commit it to the flames: for it can contain nothing but sophistry and illusion."

Hume, David: An Enquiry Concerning Human Understanding (1748)

Foreword

The manuscript of this publication is based partly on the Precision Tube Handbook of 1997 (Röytiö, H. et.al.).

The manuscript of this edition of the handbook was written by Juha Tulonen. Many other people and companies have also shared views and experiences within their special fields of expertise, including:

Herber Engineering AB, Sweden, Tube bending
Kemppi Oy, Finland, Welding

Juha Tulonen, Cold working, forming and welding, SSAB
Heidi Förell, Coatings and long-term durability, SSAB
Marco Quercini, Calculations, SSAB
Ari Minkkinen, Punching, SSAB
Tuomas Vaskuri, Laser cutting, Tibnor
Juha Rajala, HF-welding, SSAB
Lars Troive, Finite element method, SSAB
Petteri Steen, SSAB
Jussi Minkkinen, SSAB
Stephen Skate, Language revision

Many treatments, fabricating processes and equipment described in this handbook require attention to health and safety issues.

The handbook features Pro Tips to provide a summary rule of thumb:

PRO TIP: Need a change from engineering to design? Change to your own unique cross section!

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1. Introduction

This handbook is a compilation of guidelines and rules of thumb for the usability and application of technologies for longitudinally high-frequency-welded cold-formed precision steel tubes manufactured by SSAB. The tubes referred to are defined by standard EN 10305, but the properties of the tubes with regard to ultimate elongations to fracture of several steel grades exceed the requirements of this standard. Tubes according to customer specifications are also available when it comes to special cross sectional shapes or other special requirements.

Precision steel tubes manufactured by SSAB include three product groups:
- SSAB Form Tubes
- SSAB Boron Tubes
- Docol Tubes

Based on enquiries received from industries and on product presentations given by technical staff, the handbook describes the most essential tube fabrication technologies and tube properties peculiar to the manufacturing method and SSAB as a manufacturer. The beginning of the handbook discusses several partially theoretical but descriptive issues.

We trust that this handbook will give many product and production designers, developers, purchasers and innovators a useful overview of practicable upgrading technologies and support in their pursuit of cost efficiency. The right choice of tube strength and dimensions is just the start.
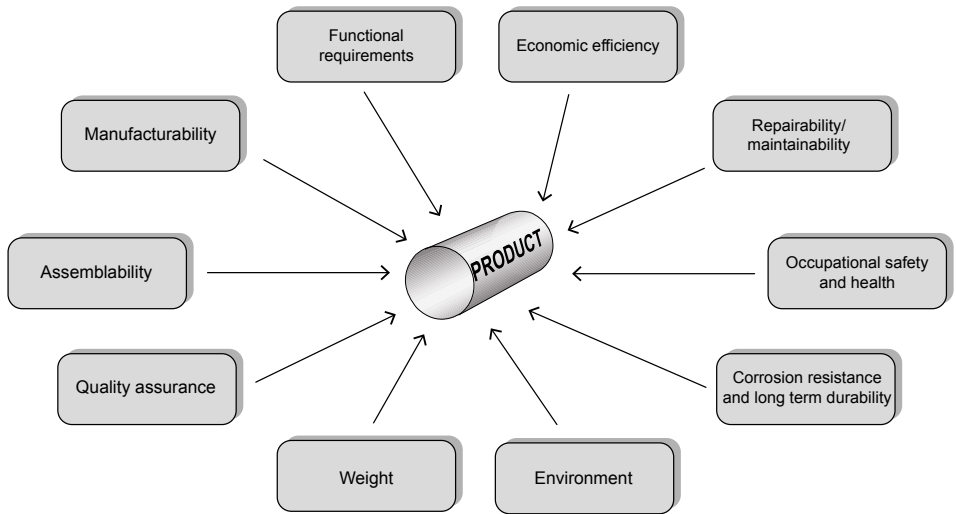
Figure 1. Some aspects affecting the quality of tubular components.

1.1 Manufacturing of longitudinally HF-welded precision steel tube

Precision steel tubes are manufactured by cold forming and high frequency (HF) induction welding, a.k.a. ERW – electric resistance welding, from hot-rolled pickled, cold-rolled or metal-coated narrow strips slit from coils on a continuous production line. Figure 2 shows the different manufacturing stages.

HFI welding

Removal of weld bead

Final inspection, marking and bundling

Oiling and cutting

Strip accumulator

Cutting and welding

Calibrating and shaping
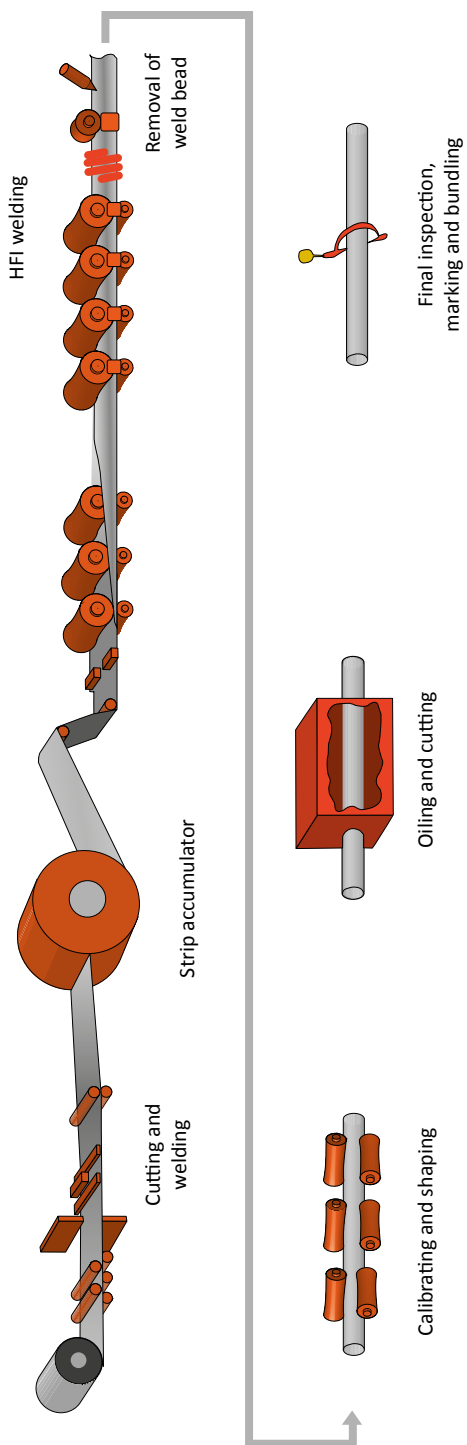
Figure 2. Principle of manufacturing longitudinally welded tube.

The steel strip passes between successive forming rolls to give it a circular shape, see Figure 3, whereupon the open slit is closed by high frequency welding. In HF-welding, a narrow zone at each edge of the strip is heated and the edges are pressed together in welding rolls without using any filler materials.

The weld is trimmed smooth externally (also internally subject to agreement) to converge with the round shape before being cooled down. If tubes are made of galvanised material, the weld seam is thermal coated after external trimming, as discussed in section 3.2.

The tube is worked to its final size, a.k.a. calibration, in a roller machine. In the profiling units, the circular tube is straightened and, when necessary, shaped into a square, rectangular or other special cross-section, see Figures 3 and 4.
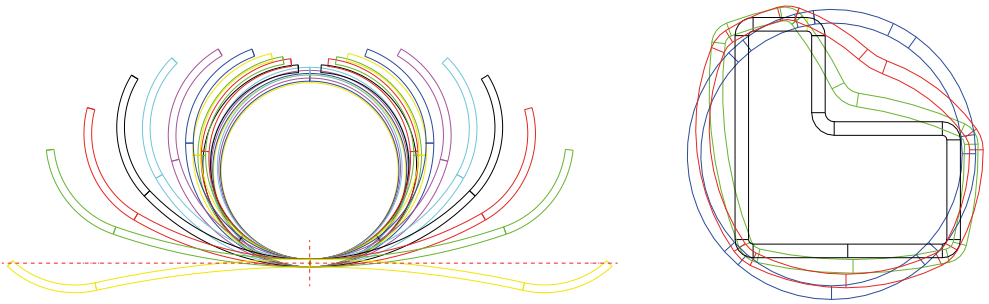
Figure 3. Forming flower showing the shaping of strip into a circular form and round tube shaping towards an angular profile.

The manufacturing process described has some features that provide the following tube characteristics:
1) strengthening of material, including tube corners, more in section 3.1.
2) presence of weld seam creating discontinuity, section 3.2.
3) unchanged material composition and structure, chapter 2.
4) improved surface quality, section 2.3.
5) introduction of corrosion resistance, sections 2.3 and 6.1.
6) achievement of dimensional precision, section 2.1.
7) retained formability capacity, chapters 2 and 3.
8) wide variety of available steel grades, section 2.
9) wide variety of available cross sections, see Figure 4.

Figure 4. Some examples of some cross section shapes available for precision tubes. Shape may be selected e.g. based on desired appearance, strength, stiffness and future fastener or weld.

PRO TIP: Need a change from engineering to design? Change to your own unique cross section!

Figure 5. Bicycle frame, including flat oval SSAB Form Tube 220 C 60x30x2.0. Courtesy of Helkama Velox Oy.

2. Steel designation and properties according to standards

One classification method for different steel tubes is according to their tensile strength, see Figure 6. This classification, of course, provides little information about their yield strength or any other properties, but gives a quick over view of available grades. SSAB neglects traditional carbon-manganese grades in its offering, mainly due to their excessive grain size and relatively poor weldability. High-strength low alloy (HSLA) grades are ferritic steels and dual phase (DP) grades contain a martensitic component in addition to ferrite in order to increase strength, but maintain comparatively good formability. As Figure 6 shows, a compromise between strength and elongation must be made.
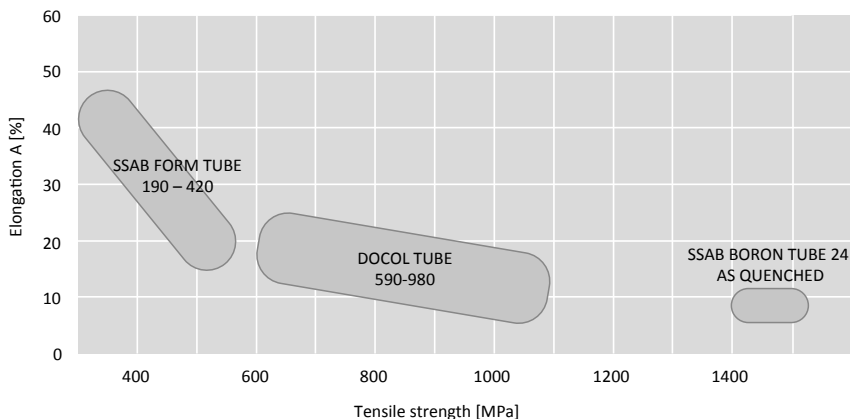
Figure 6. Steel tube grade type classification shown as a function of tensile strength and elongation.

The designation used for precision steel tube products is compliant with Parts 3 and 5 of standard EN 10305 and consists of the standard number, steel grade and delivery condition. The steel grade code refers to the steel's minimum yield or tensile strength depending on type of steel, see Tables 1, 2 and 3. The main delivery condition for SSAB's precision tubes is +CR2: welded and cold formed. The significant difference between the +CR1 delivery condition and +CR2 is the latter's supreme elongation, not to mention even higher, above standard elongation for several steel grades. An example of the designation used for SSAB's precision tube products is provided below:

Example #1

Product & bundle tag name
SSAB Form Tube 320 Z600
Test Certificate & order confirmation name
SSAB Form Tube 320 Z600
E320-CR2-S4-EN 10305-3,5

Example #2

Product & bundle tag name
SSAB Boron Tube 24
Test Certificate & order confirmation name
SSAB Boron Tube 24

Example #3

Product & bundle tag name
Docol Tube 590 GI100
Test Certificate & order confirmation name
Docol Tube 590 GI100

The tube in example #1 above is manufactured in compliance with part 3 or 5 of standard EN 10305 and its minimum yield point is 320MPa. The tube is galvanised (Z) and the minimum total mass of its internal and external zinc layer is 600g/m^2. This corresponds to an approximately 42µm zinc layer on both the inner and outer surfaces of the tube. The delivery condition of the tube is +CR2, and therefore the steel's minimum elongation according to standard is 15%. However, SSAB Form Tubes have distinctly better elongation values compared to the standard, here 23%. Table 1 shows the ultimate elongation values of SSAB Form precision tubes above standard.

The code following the product name "Docol Tube" in the designation of SSAB's high-strength precision tubes refers to the minimum tensile strength of the steel, for example, the tube designated as in example #3 above. The tube has a minimum tensile strength of 590MPa, a minimum yield strength of 500MPa and a minimum elongation of 12%, see Table 3.

Table 1. Mechanical properties (minimum values) of SSAB Form Tubes.

Steel Grade	Yield Strength $R_{p0.2}$ [MPa]	Tensile Strength R_m [MPa]	Elongation A [%]
SSAB Form Tube 190	190	270	35
SSAB Form Tube 220	220	310	28
SSAB Form Tube 320	320	410	23
SSAB Form Tube 420	420	490	14

Table 2. Mechanical properties of SSAB Boron Tube.

Steel Grade	Yield Strength $R_{p0.2}$ [MPa]	Tensile Strength R_m [MPa]	Elongation A [%]
SSAB Boron Tube 24, min.	430	450	12
SSAB Boron Tube 24, typical	470	530	23
SSAB Boron Tube 24, quenched to water, typical	1100	1500	8

Table 3. Mechanical properties (minimum values) of Docol Tubes.

Steel Grade	Yield Strength $R_{p0.2}$ [MPa]	Tensile Strength R_m [MPa]	Elongation A [%]
Docol Tube 590	500	590	12
Docol Tube 780	600	780	10
Docol Tube 980	750	980	5

For chemical compositions, see chapter 5.1.

Description of steel grade SSAB Form Tube 190:

Low-strength, very formable steel tube, for e.g. applications requiring folding and flange forming of tube end.

Class: Mild steel

Alloying: none, stabilized with Ti or Al

Structure: ferritic

Grain size: 13µm

Hardness, HV_{10}: 100

Similar sheet steel grade to raw material: SSAB Form 06, DC06 (EN 10130)

Description of steel grade SSAB Form Tube 220:

Conventional high-strength formable steel tube, for applications requiring combined strength, stiffness and formability such as furniture and household appliances.

Class: HSLA

Alloying: micro-alloyed with Ti, killed with Al

Structure: ferritic

Grain size: 8µm

Hardness, HV_{10}: 120

Similar sheet steel grade to raw material: DC02

Description of steel grade SSAB Form Tube 320:

Conventional high-strength steel tube, for applications requiring higher strength than FORM 220

Class: HSLA

Alloying: micro-alloyed with Nb, killed with Al

Structure: ferritic

Grain size: 5µm

Hardness, HV_{10}: 130

Similar sheet steel grade to raw material: HC340 (EN 10268)

Description of steel grade SSAB Form Tube 420:

High-strength steel tube for applications requiring high strength to compensate large dimensions such as in tools under high stress.

Class: HSLA

Alloying: micro-alloyed with Ti and Nb, killed with Al

Structure: ferritic

Grain size: 3.5µm

Hardness, HV_{10}: 150

Similar sheet steel grade to raw material: HC420, ZStE420 (EN 10268, SEW 093)

Description of steel grade SSAB Boron Tube 24:

Structural formable steel as delivered, uttermost high strength when hardened. For applications with abrasive conditions or where other steel grades are ruined by yielding.

Class: Hardenable

Alloying: Boron ~0.003%

Structure: ferritic as delivered, martensitic as quenched

Grain size: 8μm

Hardness, HV_{10}: 135 as delivered, 470 quenched

Similar steel grade to raw material: B24, 22MnB5

Description of steel grade Docol Tube 590:

Advanced high-strength steel tube for applications requiring high strength and formability at the level of FORM 420C.

Class: DP

Alloying: Si, Mn, Nb, Cr

Structure: ferritic-martensitic, martensite content ~10%

Grain size: 4μm

Hardness, HV_{10}: 180

Similar sheet steel grade to raw material: HCT590 (EN 10346)

Description of steel grade Docol Tube 780:

Advanced extra high strength steel for applications requiring very high strength but still some formability for applications, such as safety structures, with resistance to deformation.

Class: DP

Alloying: Si, Mn, Nb, Cr

Structure: ferritic-martensitic, martensite content ~15%

Grain size: 4μm

Hardness, HV_{10}: 230

Similar sheet steel grade to raw material: HCT780 (EN 10346)

Description of steel grade Docol Tube 980:

Advanced extra high-strength steel for applications, such as energy absorption structures, requiring superior strength.

Class: DP

Alloying: Si, Mn, Nb, Cr

Structure: ferritic-martensitic, martensite content ~20%

Grain size: 4μm

Hardness, HV_{10}: 280

Similar sheet steel grade to raw material: HCT980 (EN 10346)

Figure 7. Cable ladder manufactured using a special tube profile. Courtesy of Meka Pro Oy.

Figure 8. Shop fitting system with horizontal long-span beams manufactured using a special tube profile. Courtesy of Constructor Finland Oy.

PRO TIP: Yield strength, tensile strength and elongation values for each delivery can be found on the test certificate.

2.1 Technical delivery conditions

SSAB precision tubes are delivered in accordance with the standards listed in Table 4. Properties, e.g. minimum mechanical properties, exceeding the standard are available subject to contract. For the latest manufacturing programme, recommended dimensions or tubes in stock, please see SSAB's website, sales or the nearest stockist.

Table 4. Steel tubes for precision applications. Technical delivery conditions.

Cross section	Technical delivery conditions
Round tubes	EN 10305-3
Square and rectangular tubes	EN 10305-5
Oval, flat oval and other special shapes	EN 10305-5

The surface of precision tubes is lightly oiled to protect it from corrosion during transport and short-term storage. Tubes can be delivered dry on request, but in such cases SSAB will not be responsible for any possible rust.

2.1.1 Dimensional tolerances

Tables 5, 6 and 7 show the dimensional tolerances SSAB precision tubes, which exceed the tolerances of many other tubular products. This is extremely beneficial when reducing production scrap in tube forming, using robotised welding, reducing the number of tools needed due to clearance requirement, minimizing setup and adjustment times or designing products with utmost tolerances. Also all kinds of inserts, connections and plugs can be included at higher quality and lower costs.

Table 5. SSAB diameter tolerances, round tubes.

OD	SSAB
D < 20 mm	± 0.12 mm
20 ≤ D < 32 mm	± 0.15 mm
32 ≤ D < 44 mm	± 0.20 mm
44 ≤ D < 55 mm	± 0.25 mm
55 ≤ D < 70 mm	± 0.30 mm
70 ≤ D < 80 mm	± 0.35 mm
80 ≤ D < 100 mm	± 0.40 mm
100 ≤ D < 108 mm	± 0.50 mm
108 ≤ D < 127 mm	± 0.60 mm

Table 6. SSAB outside tolerances, square and rectangular tubes.

H	SSAB
H ≤ 25 mm	±0.20 mm
25 < H ≤ 35 mm	±0.25 mm
35 < H ≤ 50 mm	±0.30 mm
50 < H ≤ 60 mm	±0.35 mm
60 < H ≤ 70 mm	±0.40 mm
70 < H ≤ 80 mm	±0.50 mm
80 < H ≤ 90 mm	±0.60 mm
90 < H ≤ 100 mm	±0.65 mm
100 < H ≤ 150 mm	±0.70 mm

Table 7. SSAB tolerances versus standard EN 10305 tolerances.

	EN 10305	SSAB
Mill length (5000-8000 mm) Standard length 6000 mm	-0 mm / +100 mm	-0 mm / +50 mm, Special tolerances by request
Height of internal bead, not scarfed		g < 0.6 mm, when T ≤ 1.5 mm g < 0.4 x T, when 1.5 mm < T < 4.0 mm
Straightness	<0.20% of measured length	< 0.15% of measured length

2.1.2 Better elongation at fracture

SSAB Form Tubes have better elongation at fracture than standard tubes, see Table 8. This gives an enormous advantage in product design, energy absorption, flexible and reliable production, etc.

Table 8. Minimum mechanical properties of SSAB Form Tubes and and tubes according to standard EN 10305.

Steel grade	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]
E190+CR2	190	270	26
E195+CR1	195	330	8
SSAB Form Tube 190	**190**	**270**	**35**
E220+CR2	220	310	23
E235+CR1	235	390	7
E235+N	235	340	25
SSAB Form Tube 220	**220**	**310**	**28**
E320+CR2	320	410	19
SSAB Form Tube 320	**320**	**410**	**23**
E420+CR2	420	490	12
SSAB Form Tube 420	**420**	**490**	**14**

2.2 Inspection documents

Delivery of SSAB precision tubes is always accompanied by a test report "type 2.2" according to standard EN 10204. This test report includes the mechanical test values of the manufacturing processes used. By agreement, tubes are also supplied with a "type 3.1" inspection certificate. SSAB's tube test report and inspection certificate both include additional features to the standard requirements, see below.

Standard test report "type 2.2"

This report is a document which certifies that the products supplied meet the requirements of the order and gives the test results based on non-specific inspection and testing. Non-specific inspection refers to inspections carried out by the manufacturer in accordance with their own procedures to assess whether products made by the same manufacturing process meet the requirements of the order. The products inspected may not necessarily be the products actually supplied. A test report does not necessarily include mechanical properties or the chemical composition of the products delivered. Tensile test

results, drift expansion test results and chemical composition may refer to other products or a manufacturing lot other than that delivered.

SSAB test report "type 2.2"

When SSAB provides a test report, it additionally includes the manufacturing procedure to the standard test report. NDT testing of each individual tube, dimension specific flattening and drift expansion testing, steel grade specific flattening and drift expansion testing, dimension specific tensile testing and steel grade specific tensile testing. Additionally, chemical composition refers to products delivered and tensile test results to manufacturing lot delivered. Residual quantities according to EN 10305 apply.

Standard inspection certificate "type 3.1"

This document certifies that the products supplied are in compliance with the requirements of the order and gives the test results. The inspection unit and the test to be carried out are determined by the product specification, official regulations and corresponding technical rules and/or by the order. The document is validated by an authorised representative of the manufacturer independent of the manufacturing department. In a type 3.1 inspection certificate, the manufacturer is entitled to present specific test results originating from a previous stage in the production process provided that the processing stages are traceable and that the corresponding original inspection documents are available. This means e.g. that tubes manufactured from each raw material coil are tensile tested within each manufacturing lot. It is possible that the inspection certificate does not include chemical composition of the tubes delivered. Inspection certificates are dimension and steel grade specific.

SSAB inspection certificate "type 3.1"

When SSAB delivers an inspection certificate, the manufacturing procedure includes coil specific chemical composition and coil specific dimension measurements in addition to standard test report 2.2, SSAB test report 2.2 and standard inspection certificate 3.1. Inspection certificates include tensile test results and chemical composition of the tubes delivered. Residual quantities according to EN 10305 apply.

2.3 Surface condition, roughness and coating thickness

Depending on application and availability, surface condition of the tube is normally selected based on surface roughness and corrosion protection, see Tables 9, 10 and 11. The condition of a cold-rolled surface is smoother than a hot-rolled pickled surface. A cold-rolled surface is more convenient for

chrome plating and other coating methods, where high cost surface treatment substances are present. A hot-rolled pickled surface may be a good choice for a painting substrate. Metal coating comes with many alternative characteristics: more about S4 type metal coatings in chapter 6.

Usually the R_a value is used when measuring the surface roughness of a tube. Cold working as a tube manufacturing method exerts vast surface pressure on steel strip. When this surface pressure is combined with smooth forming and calibration rolls, the R_a value will decrease. The amount of roughness change is generally relative to the cold working rate, which means that tubes with a small D/T ratio tend to have smaller roughness.

Table 9. Surface conditions of precision steel tubes manufactured by SSAB.

According to EN 10305	Meaning	SSAB manufacturing definition for tube's raw material	Example of identification of SSAB Form Tube	Example of identification of Docol Tube
S2	Pickled	Hot rolled and pickled	SSAB Form Tube 220 H	Docol Tube 780 H
S3	Cold rolled	Cold rolled, annealed and temper rolled	SSAB Form Tube 220 C	Docol Tube 780 C
S4	Coated	Metal coated, Z/GI	SSAB Form Tube 220 Z	Docol Tube 780 GI
		Metal coated, ZA	SSAB Form Tube 220 ZA	Docol Tube 780 ZA
		Metal coated, ZF/GA	SSAB Form Tube 220 ZF	Docol Tube 780 GA

Table 10. Surface roughness

Surface	Roughness R_a [µm]	Suitable application
H	<2.0	Painting, galvanizing
C	<0.6	Painting, chrome plating, galvanizing
Z/ZA/ZF/GI/GA	depending on precise coating	Corrosion protection

Table 11. Metal coatings, coating thicknesses and mass. Mass is the minimum total coating mass on both surfaces in triple spot tests. Recommended series are bolded.

Thickness [µm], each side of wall	Zinc (Z/GI) [g/m²]	Galfan (ZA) [g/m²]	Galvannealed (ZF/GA) [g/m²]
7	100	95	**100**
8	-	-	**120**
10	140	130	140
20	**275**	**255**	-
23	-	300	-
25	350	-	-
32	450	-	-
42	600	-	-

Figure 9. Cage trolleys for logistics, warehousing and in-store efficiency. Courtesy of K. Hartwall Oy Ab.

2.4 Strength, R_p/R_m-ratio

Characteristics defined by tensile test are yield strength (R_p) and tensile strength (R_m). Yield strength is sometimes also called yield point. Tensile strength is sometimes called ultimate tensile strength or ultimate strength. With steels delivered as hot rolled or heat treated, there is lower (R_{eL}) and upper (R_{eH}) yield strength, but with cold-formed steel tubes after work hardening, the R_p value is applicable. It is established practice that $R_{p0.2}$ is used for measurement and test reporting.

The single axis tensile test is the most common and the simplest mechanical test and, due to its simplicity, is used as a quality control method for tube manufacturing lots. In the test, a tensile test sample, cut from a steel tube or whole tube, is stretched with force F [N] and the sample elongation Δ [mm] is measured by using a gauge length L_0, see Figure 10.

Yield strength is the stress after elastic deformation and before plastic deformation, meaning that prior to the yield strength of the material, the tube will return to its original shape and length when the stress is removed. Tensile strength is the maximum stress a tube can withstand before breaking.

By calculating yield strength – tensile strength –ratio (R_p/R_m), the remaining work hardening capacity of the tube can be estimated, see chapter 3.5 for "n" value. With heavily cold-formed tubes, yield strength may be almost equal to tensile strength, in other words, the R_p/R_m ratio may be close to 1. This is considered a drawback in many building regulations such as Eurocode 3, but in practice with many precision tube applications this is not a problem due to the tube's high total elongation values and possibilities to compensate early necking by changes in the cross-sectional shape, e.g. during tube bending, thinning of the tube wall is partly compensated by shape changing. It should be noticed that while two different tubes may have the same R_p/R_m-ratio, one may have higher total elongation. The R_p/R_m-ratio correlates with uniform elongation and can be used to estimate it.
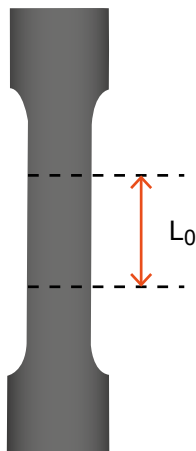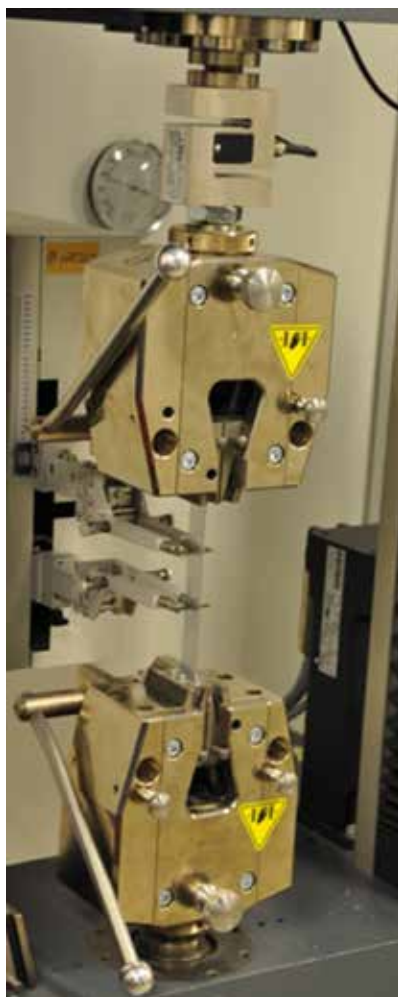
Figure 10. Tensile test setup and test piece geometry.

2.5 Elongation after fracture and uniform elongation

Elongation after fracture, or in other words, elongation at fracture, ultimate elongation or total elongation, is one of the material parameters determined by the tensile test. Elongation after fracture is expressed as a percentage of the original test sample gauge length. Table 12 shows some different elongation definitions.

Table 12. Elongation definitions.

Symbol	Definition
A_5	Percentage elongation after fracture, replaced by A when ISO 6892-1:2009 replaced EN 10002-1:2002.
A	Percentage elongation after fracture former A_5. Original gauge length equal to $5.65\sqrt{S_0}$, which is called "proportional gauge length". Usual gauge length for tube materials.
A_{80}	Percentage elongation after fracture of a gauge length 80 mm. Usual gauge length for plate, coil and sheet materials.
A_{50}	Percentage elongation after fracture of a gauge length 50 mm. Often replaces gauge length equal to 2 inches.
A_x	Percentage elongation after fracture of non-proportional test place, subscript "x" indicating gauge length in millimeters.
A_{gt}	Total extension force, for practical purposes values are very close of A_g
A_g	Plastic extension at maximum force, in other words uniform elongation. Related to work hardening exponent "n". Is corresponding elongation value for tensile strength value.

Due to necking of the tensile test sample, the elongation value after fracture is strongly dependent on gauge length. This is because the thicker the test piece is, the wider the necking area will be. The shorter gauge length will generally elongate more within gauge length, resulting in a greater measured value, a.k.a. very short gauge length and will contain nothing but the necked sample area. The very long gauge length will contain necked area plus non-necked area, see Figures 11 and 12. The same phenomenon occurs e.g. with sheet materials: A_{80} for thin sheet is not directly comparable with A_{80} for thick sheet. Additionally, to add to the confusion, thinner sheet materials have a tendency to realise lower elongation values than thicker sheet materials.

There are standard gauge lengths defined internationally, e.g. 80 mm, and so called proportional gauge length, which is dependent on cross-sectional area of the test piece, $L_0 = 5.65\sqrt{S_0}$. In practice, it is not always possible to use the most desired gauge length. Also, depending on final product application, there is sometimes an interest in several different ultimate elongations of different gauge lengths. Furthermore, since elongation after fracture between sheet, e.g. A_{80}, and tube materials, e.g. A, cannot be directly compared, a method for elongation conversions is needed.

thin test piece   thick test piece
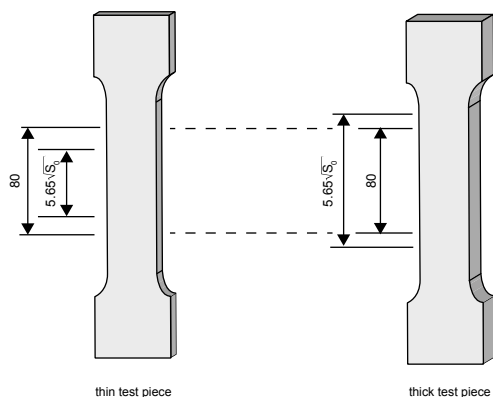
Figure 11. Difference between different gauge lengths for thin and thick test pieces to determine elongations A (proportional) and A_{80} (non-proportional).

thin test piece   thick test piece
narrow necking area   wide necking area
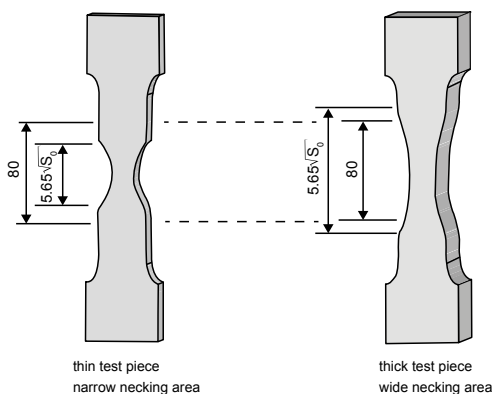
Figure 12. Difference between necked and non-necked test piece areas within different gauge lengths nearing the end of the tensile test.

Product standard EN 10305-5 says that "If a non-proportional test piece is used, the percentage elongation value shall be converted to the value for a gauge length using the conversion tables given in EN ISO 2566-1." Anyhow, standard EN ISO 2566-1 says that elongation conversions are not applicable to cold-reduced steels. Cold-formed tubes are not cold reduced to the letter, but it has been noticed that the 0.4 value of the exponent in the Oliver formulae used in EN ISO 2566-1 for conversions is not always true for cold-formed tubes with a high degree of deformation, a.k.a. cold working rate. In practice,

the exponent in the Oliver formulae is somewhat higher. This leads to the conclusion that conversions to shorter gauge lengths, e.g. $A_{50} => A_{30}$, end up with too small values and conversions to longer gauge lengths, e.g. $A_{50} => A_{80}$, end up with too high values. See also chapter 3.9 for the definition of true elongation.

PRO TIP: Elongation A is not equal to elongation A_{80}.

Figure 13. Felling lever with a tubular shaft of high-strength steel for wood logging. Courtesy of Fiskars Oyj.

3. What is not seen on product standards

Technical delivery conditions define a product and provide strict limits for the specific properties agreed. This is good information, but experimental data of the properties realised is preferred. Sometimes this is not quite enough for a tube upgrader when carrying out product design, production process, tooling design or final product properties. This is why it is important to see beyond documents and give some thoughts to what lies behind them, what conclusions may be drawn from them or what other information a tube manufacturer may have to help utilise the full benefits of tubular steels. Fabrication simulation - whether a computer model, notebook sketch or visualisation in the mind - often requires both constants and variables, which are discussed in this chapter. On today's high-performance computers, the problem with carrying out simulations is not calculating time, but the correct starting data.

3.1 Tube diameter – thickness ratio, D/T

Because of the cold-roll-forming technology used in tube manufacturing, the effect of cold working or work hardening effects on steel material and final tube properties should be considered.

Roll forming of tubes is basically elastic-plastic bending, including several deforming steps within the forming, calibrating and shaping processes. When bending a steel strip, the yield strength of the material is exceeded and plastic deformation takes place on the surfaces: tension on the outer surface and compression on the inner surface. The smaller the tube diameter is, the smaller the bending radius of strip is compared to material thickness. Correspondingly, the thicker the steel strip is, the smaller the bending radius is compared to the tube diameter or tube radius. This cold working rate can be described by using a tube diameter – thickness ratio: D/T.

Using a D/T ratio suggests that when considering cold working or work hardening, it is not the actual tube dimensions that are important, but their relation to each other. For example, tubes 20x1 and 40x2 both have a D/T ratio of 20 and have been cold worked by a roughly similar amount.

When using the same steel grade or strip material for manufacturing tubes, the tube properties differ from each other because their dimensions and properties also differ from e.g. the mechanical properties defined by the

standard. Of course, e.g. yield strength will be according to the standard, but may differ a lot from the minimum value given by the standard. Likewise, elongation values meet standard requirements, but actual values may be significantly higher, see Figures 14...19.
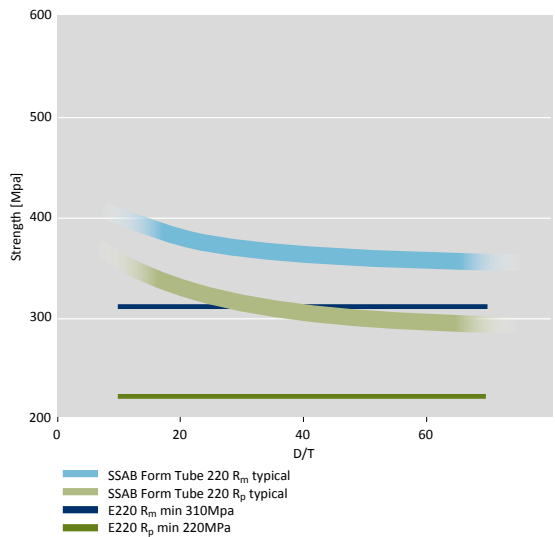

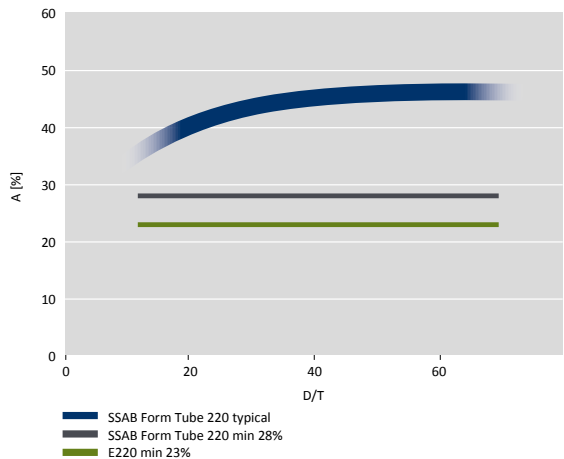**Figure 14.** Yield and tensile strength of SSAB Form Tube 220.

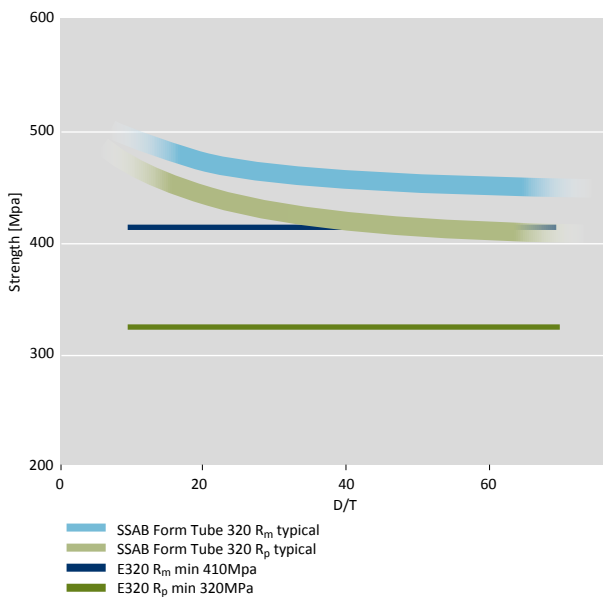**Figure 15.** Elongation value A of SSAB Form Tube 220.

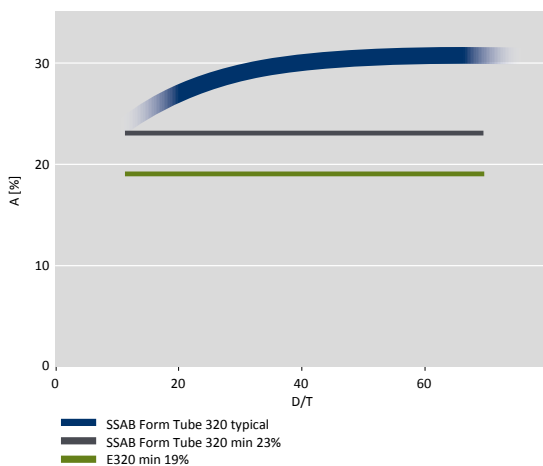**Figure 16.** Yield and tensile strength of SSAB Form Tube 320.
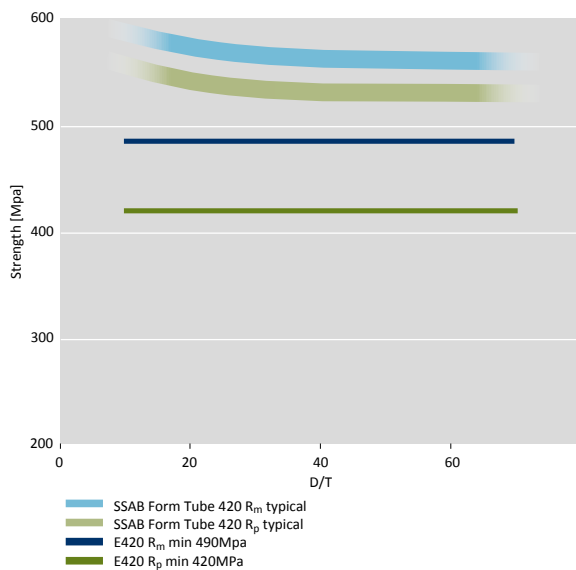

Figure 17. Elongation value A of SSAB Form Tube 320.

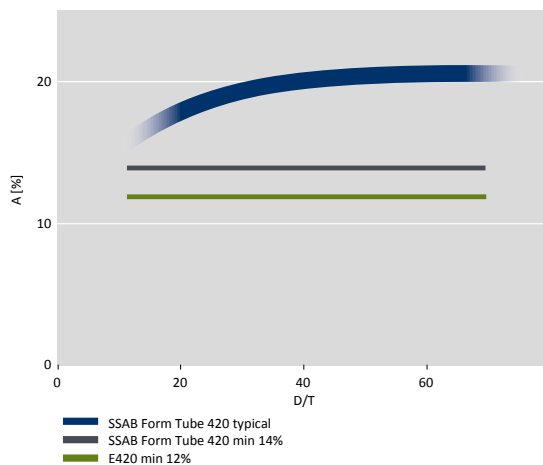**Figure 18.** Yield and tensile strength of SSAB Form Tube 420.

Figure 19. Elongation value A of SSAB Form Tube 420.

3.2 Weld properties

Precision tubes are longitudinally welded using high frequency induction welding (HF) process. Special characteristics for this welding process are that no filler and no shield gas is used, and due to high efficiency and a high welding speed, the heating and cooling rates are high. As a result, the weld is of high quality and HAZ is narrow.

3.2.1 Weld and heat affected zone (HAZ)

As already described in the tube manufacturing process, on the tube line the flat strip is fed into the forming rolls and shaped into a nearly complete tube. As the formed strip passes through the coil, a high frequency current flows at the edges and the steel's resistance causes the very edges of the strip to start to heat quickly and reach melting point. These edges are forged together as they pass between the weld rolls and molten metal is squeezed out and the clean metal surface forms a weld.

Due to the special characteristics mentioned above, the HAZ of a precision tube is fairly narrow compared to common fusion, for example with MIG/MAG, welds. The HAZ width is typically about 1mm and, since no filler is used, the HAZ structure consists of a very narrow fusion line, grain growth zone, grain refined zone, partially transformed zone, zone of spheroidal carbides and the base material.

Also high efficiency and the high welding (manufacturing line) speed mean that the heating and cooling rates are very high. It usually takes somewhat more than a second to heat up to melting point, form a weld and then cool down to almost room temperature. These extremely fast thermal cycles favour low levels of hardening elements, especially carbon and manganese, in order to avoid martensitic and thus high hardness weld structures. Low alloying elements in SSAB Form Tubes form bainitic structures in the HF-weld and these structures have far better processing properties (for example drilling, cutting) than a martensitic structure.

It is also extremely important to have low levels of impurities in the steel, especially sulphur. These impurities can form a band which, during HF-weld formation, turns into the outer surface and in processing this band crack lacks deformability. The sulphur content of SSAB Form Tubes is always below 0.025%.

In order to obtain a robust quality weld, there must be a very thin layer of molten material in the edges forming the weld. The edges must then be pressed hard enough together by the welding rolls to squeeze all the molten

material out of the fusion line, see Figures 20-22. Because of the electrical properties of high frequency welding, the heat affected zone has an hourglass shape. In the welding process outside and inside, burrs are formed due to this formation of pressure on the weld. An outside burr is scarfed out and in most cases there is option for inside burr removal. High-strength steels in particular need more pressure from welding rolls to ensure a high-quality weld and thus the inside weld burr of these grades is often slightly higher than with ordinary steel grades. Besides sufficient welding roll pressure, the meeting angle the strip edge has a major effect on weld quality, see Figures 21 and 22.

Base material
Heat affected zone (HAZ)
Molten steel squeezed out to the burrs
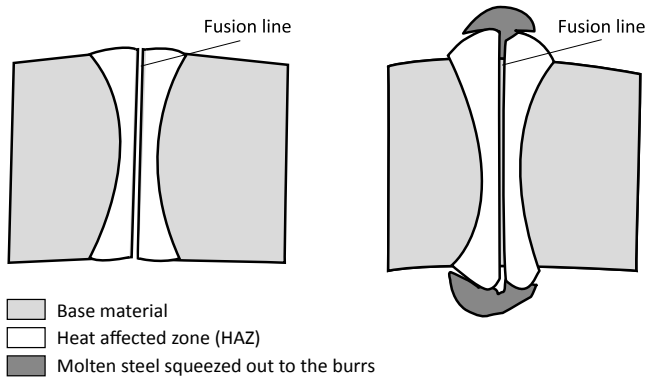
Figure 20. Formation of an HF-weld, before outside scarfing.

Precision tubes typically have smaller inside burrs than structural hollow sections because of lower wall thicknesses and customer applications preferring further processing that benefit low inside burrs, for example, bending and telescoping. However, enough molten material is always needed to be squeezed out to ensure a quality weld.

Figure 21. Example of a high-quality HF-weld: The edges are at the same level, and the inside burr shows there has been enough welding energy and squeeze pressure to create a quality weld.
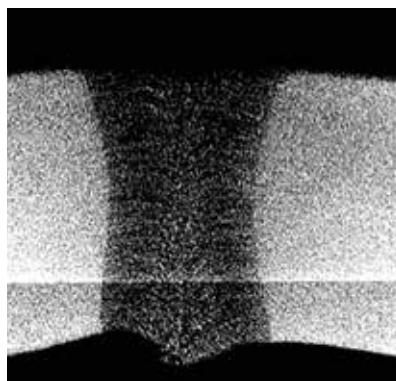
Figure 22. Example of a poor HF-weld: The edges are not at the same level and the welding energy and squeeze pressure were insufficient to form a quality weld.

3.2.2 Strength and hardness of the weld

Because of the extremely fast heating and cooling rates, the HAZ of a high frequency weld has, in most steel grades, slightly higher hardness than base material, see Figures 23 and 24. To ensure good processing properties, e.g. cutting and drilling, the balance of chemical components is very important - the more hardening elements in the steel, the higher the HAZ hardness.
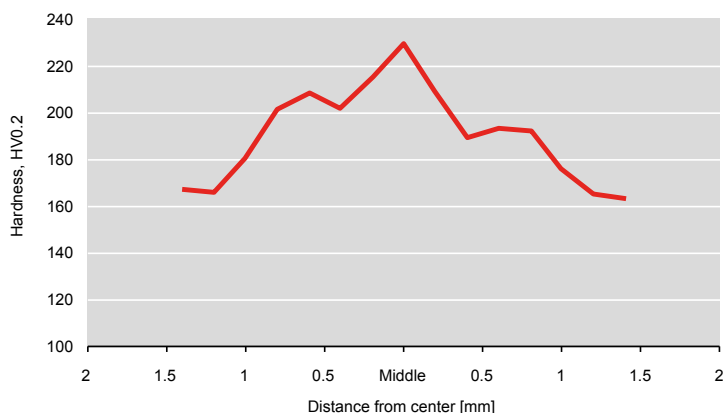
Figure 23. Hardness profile of SSAB Form Tube 220. Hardness level at each end of the line represents the base material hardness.
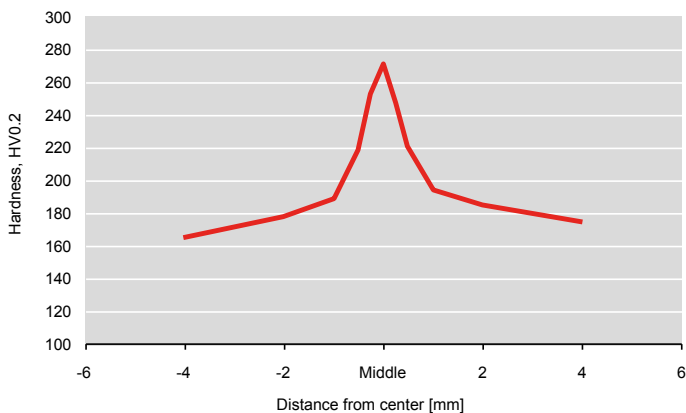
Figure 24. Hardness profile of SSAB Form Tube 420. Hardness level at each end of the line represents the base material hardness.

Due to a longitudinal, but very narrow, HAZ in precision tubes, the weld usually does not affect the processing properties in the transverse direction of the weld. However, in the longitudinal direction, the slightly higher hardness and strength of the HAZ can cause some limitations, for example, if the whole tube has to be stretched very much longitudinally. In high-strength steel grades, including and over Docol Tube 590, there can be very narrow zones in the HAZ that can have slightly lower hardness and strength than the base material. However, in most cases these can be taken into account in the design, see Figure 25.

Figure 25. Hardness profile of Docol Tube 590 tube. The tube is inside scarfed and the hardness level at each end of the line represents the base material hardness.

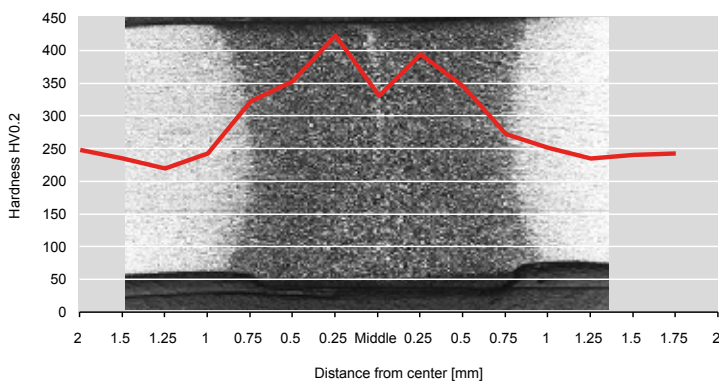The differences in the maximum hardness of the HAZ are based mostly on differences in alloying elements but also on the strength level of the base materials.

3.2.3 Weld position and corrosion protection

The weld is usually positioned on the narrow side of a rectangular precision tube. However, there are usually several possibilities to place the weld on the other side or places (also in square, flat oval, tubes, etc.), where this is beneficial for the design. Figure 26 shows some examples of possible weld positions. Most often the weld is placed away from areas that are to be drilled during processing.

8 +/- 4 mm

18 +/- 4 mm

Figure 26. Possible weld seam positions and tolerances.

The outside burr is always scarfed out and this area differs to some extent from the other outside surface. The inside burr can usually be scarfed out, but this requires additional tooling and setup on the tube manufacturing line.

If the precision tube is made of metal-coated, e.g. galvanised, strip, the heat generated during the welding process, coupled with the tooling operation to remove the weld fins, destroys the tube coating around the weld area. Re-protection of weld damage is achieved by applying a metal sprayed deposit that matches the tube coating. A spraying system to repair the weld area is installed onto the tube mill. In the spraying process, a pair of metal wires is melted by an electric arc. The molten material is atomised by a cone of compressed air and propelled onto the weld seam. This spray solidifies when it hits the surface of the tube to form a dense coating, which re-coats the tube weld area to protect against corrosion. Figure 27 shows a schematic diagram of the weld protection of SSAB Form Tube Z275. SSAB uses zinc and aluminium wires to protect the weld. The wire's weight percent is 85% zinc and 15% aluminium. The volume fraction is 50% zinc and 50% aluminium. It is also possible to use zinc-aluminium alloyed wires or only zinc wires. The weld protection corrosion resistance is as good as the corrosion resistance of the basic material.
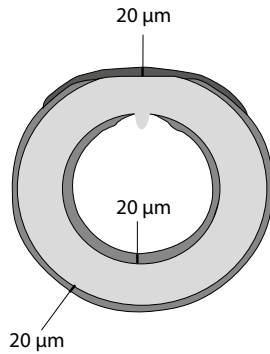
Figure 27. Schematic diagram of the weld protection of SSAB Form Z275.

Figure 28. Electric wire arc thermal spray system: console and power supply and spray gun. Reproduced by permission of Oerlicon Metco.

3.3 Impact strength

Impact strength gives a measured value for the capacity of the material to absorb energy, in other words, define toughness, ductility or cold embrittlement behaviour of the material.

Cold embrittlement evaluation is ordinarily based on the Charpy impact test, also known as Charpy v-notch test, according to EN 10045-1. There are also corresponding ASTM and ISO standards. The Charpy-test is a standardised high strain-rate test which determines the amount of energy absorbed by a material during fracture. Absorbed energy is a measure of a given material's notch toughness and acts as a tool to study temperature-dependent brittle-ductile transition. The standard defines Charpy-specimen dimensions as 10x10x55 mm. The standard also says that "if standard test pieces cannot be obtained from the material, a reduced section test piece, with a width of 7.5 mm or 5 mm shall be used…" The reason to constrict the minimum test piece width, and thus in practice the minimum thickness of the steel studied, is that in the Charpy test, the test piece fracture occurs under the triaxial state of stress on the plane, in other words, uniaxial state of strain. When using the Charpy method to test thin steel material, e.g. thickness of 2 mm, the thin test piece is under a state plane stress and a multiaxial strain state. Due to the change in the state of stress and strain when shifting from thick to thin material thicknesses, the test results are not comparable. In other words: if the material is tested in two different ways, the results cannot be compared.

Also, when using a thinner test piece, the probability of the initiation of brittle fracture is smaller, e.g. there are not any inclusions inside the steel in the line of the V-notch, and the test result might be too optimistic. Some rules allow a direct extrapolation of thin piece impact energy by multiplying it by a correcting factor. There is also SINTAP-based impact strength correction method for small test pieces.

On the other hand, it is known that increasing the carbon content will increase the transition temperature, and thus tendency to brittle fracture, of the steel. Also it is known that increasing the manganese content will decrease the transition temperature and the Mn/C ratio should be at least 3:1 for satisfactory impact strength. For example, the carbon and manganese contents of tube steel grade SSAB Form Tube 420 C are typically 0.06% (so-called low carbon steel) and 1.00% respectively, giving an Mn/C ratio of 17. Also, this steel grade has a very low phosphorus content and sensible silicon content, which point to good impact strength values in the metallurgical sense. SSAB Form 420 C steel grade is alloyed with niobium and has a small grain size (~3.5μm), which means low transition temperature and good impact strength.

As mentioned above, the triaxial stress state cannot be achieved with thin steel material in Charpy testing. On the other hand, it could be very difficult to obtain a similar triaxial stress state to that in the Charpy test with thick material, in real applications, with real components or with parts manufactured out of thin steels. Thus, the whole concept of impact strength as it is understood with reference to the Charpy test might be irrelevant.

So, for the reasons mentioned above, the impact strength of precision tubes is not measured, nor is the minimum value for impact strength guaranteed, but SSAB Form and Docol steel grades can be expected to have a fair resistance against brittle behaviour in conventional applications. See Table 14 for the carbon, manganese, phosphorus and silicon content and Table 17 for the grain sizes of Form Tubes. Tables 16 and 19 show the corresponding composition and grain size of Docol Tubes. For specification of chemical composition, please see Table 27.

Table 14. Carbon, manganese, phosphorus and silicon content of cold-rolled SSAB Form Tubes. Typical values.

Steel grade	C [wt%]	Mn [wt%]	P [wt%]	Si [wt%]	Mn/C
SSAB Form Tube 190	0.005	0.40	0.01	0.01	80
SSAB Form Tube 220	0.06	0.40	0.01	0.01	7
SSAB Form Tube 320	0.07	0.70	0.01	0.01	10
SSAB Form Tube 420	0.06	1.00	0.01	0.20	17

Table 15. Carbon, manganese, phosphorus and silicon content of cold-rolled SSAB Boron Tube 24. Typical values.

Steel grade	C [wt%]	Mn [wt%]	P [wt%]	Si [wt%]	Mn/C
SSAB Boron Tube 24	0.22	1.10	0.02	0.20	5

Table 16. Carbon, manganese, phosphorus and silicon content of cold-rolled Docol Tubes. Typical values.

Steel grade	C [wt%]	Mn [wt%]	P [wt%]	Si [wt%]	Mn/C
Docol Tube 590	0.11	0.90	0.015	0.40	8
Docol Tube 780	0.12	1.50	0.015	0.20	13
Docol Tube 980	0.15	1.50	0.015	0.50	10

Table 17. Grain size of SSAB Form Tubes. Typical values.

Steel grade	Grain size [µm]
SSAB Form Tube 190	13
SSAB Form Tube 220	8
SSAB Form Tube 320	5
SSAB Form Tube 420	3.5

Table 18. Grain size of SSAB Boron Tube 24. Typical values.

Steel grade	Grain size [µm]
SSAB Boron Tube 24	8

Table 19. Grain size of Docol Tubes. Typical values.

Steel grade	Grain size [µm]
Docol Tube 590	4
Docol Tube 780	4
Docol Tube 980	4

3.4 Stress-strain curve, plastic material model, physical properties

Standard datasheet information about a tube's properties is on general level and does not provide sufficient information about the tube when simulating component fabrication. In addition, regarding what was discussed concerning mechanical properties evaluated by tensile test in chapter 2, there is a need to study the stress-strain curve, sometimes called a flow curve, and some properties adapted from that. A true stress-true strain curve is an essential part in defining material, especially for semi-dynamic simulation purposes.

Some production technologies and part geometry are growing increasingly complicated because of the pursuit to lower overall costs per part, taking into consideration tooling costs, material costs and the number of parts processed. In the case of complex component fabrication, product manufacturability is difficult to estimate and empirical design principles are not always sufficient, see Figure 29.
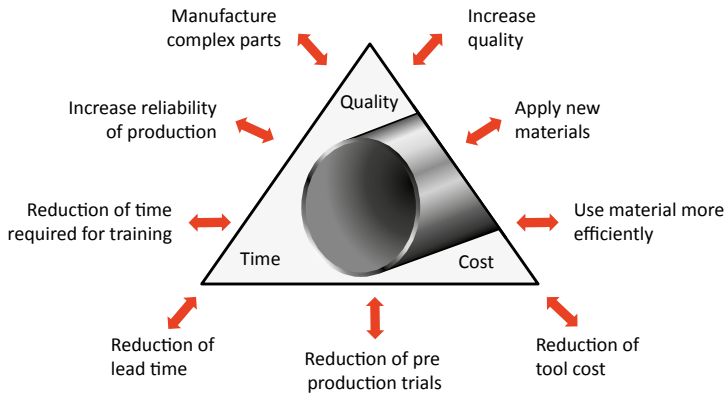
Figure 29. Complexity of part fabrication.

A tensile test gives a dependence between the measured force, F [N], and movement, L [mm], which are converted to stress [R] and elongation [e] as in equations (1) and (2) with the help of the original cross sectional area of the test piece S_0 [mm²] and original gauge length L_0 [mm].

$$R = \frac{F}{S_0} \tag{1}$$

$$e = \frac{L_u - L_0}{L_0} = \frac{\Delta L}{L_0} \tag{2}$$

If the change in the cross sectional area, that is momentary cross section S, and the change of movement of the test piece are observed incrementally, true values for stress and elongation can be shown, as in equations (3) and (4).

$$\sigma = \frac{F}{S} \tag{3}$$

$$\varepsilon = \int_{L_0}^{L_u} \frac{dL}{L} = \ln\left(\frac{L_u}{L_0}\right) \tag{4}$$

There is a fundamental difference between nominal and true strain, which becomes evident when the sum of the total strain of the partial strains is calculated. The nominal total strain does not equal the sum of nominal strains, but the true total strain does equal the sum of the true strains, see equations (5) to (10).

1st partial strain:

$$(L_1 - L_0)/L_0 \tag{5}$$

Summed with 2nd partial strain:

$$(L_2 - L_1)/L_1 \tag{6}$$

Is different from:

$$(L_2 - L_0)/L_0 \tag{7}$$

But 1st partial true strain:

$$ln\left(\frac{L_1}{L_0}\right) \tag{8}$$

Summed with 2nd partial true strain:

$$ln\left(\frac{L_2}{L_1}\right) \tag{9}$$

Is equal to total true strain:

$$ln\left(\frac{L_2}{L_0}\right) \tag{10}$$

Ultimate tensile strength corresponds to uniform elongation:

$$R = \frac{F_m}{S_0} \tag{11}$$

True and nominal stress and strain values are related up to uniform elongation:

$$\varepsilon = ln(1 + e) \tag{12}$$

$$\sigma = R(1 + e) \tag{13}$$
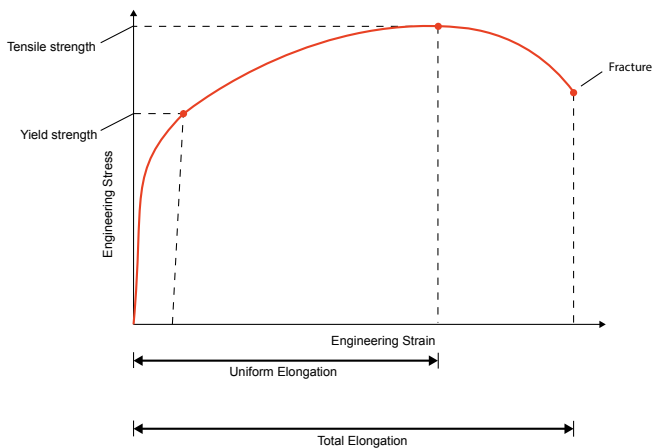
Figure 30. Tensile test curve illustration.

When presenting this stress-elongation dependence in one figure, we see something like that in Figure 31 for different materials.
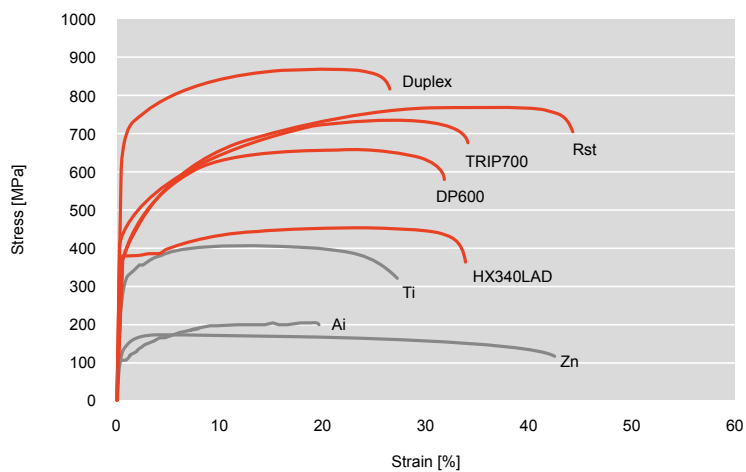
Figure 31. Stress-elongation relation for different material categories.
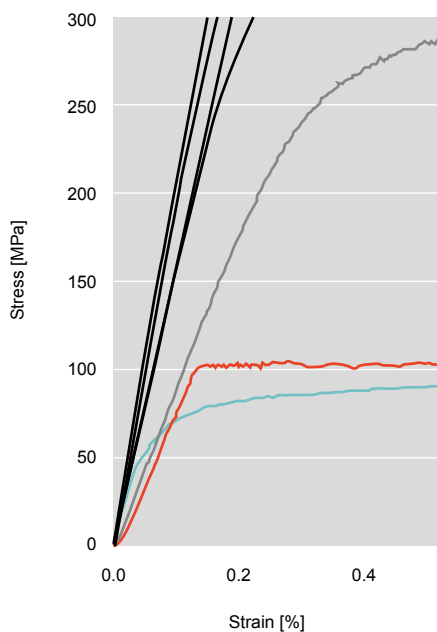
When zooming into the beginning of the stress-strain curve, the difference in Young's modulus, a.k.a. the modulus of elasticity, is present, see Figure 32.

Figure 32. Young's modulus of different materials. The curves are zoomed parts from Figure 31.

Young's modulus may be a little different for different HSLA steel grades and may also change due to the degree of deformation, but generally e.g. for FEM simulation purposes it is quite accurate to say E=210GPa. Aluminium has a Young's modulus of ~70GPa, which make its stiffness and deflection behaviour completely different, see Case study 3.8.
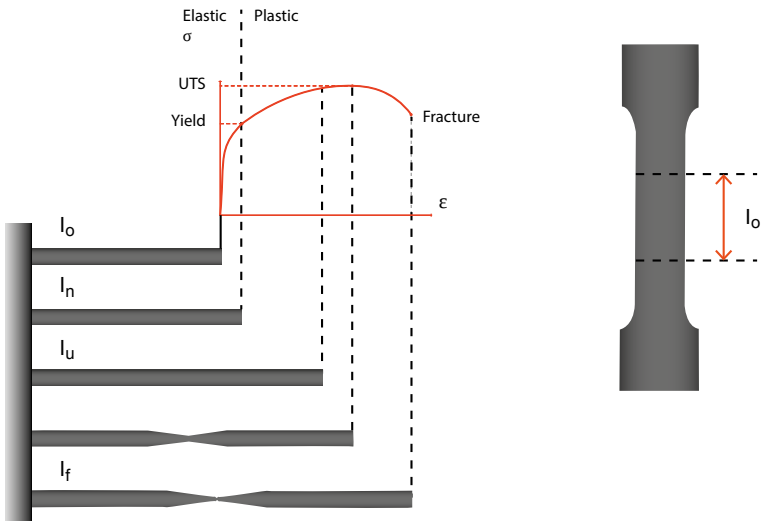
Figure 33. Yielding and necking of steel sample.
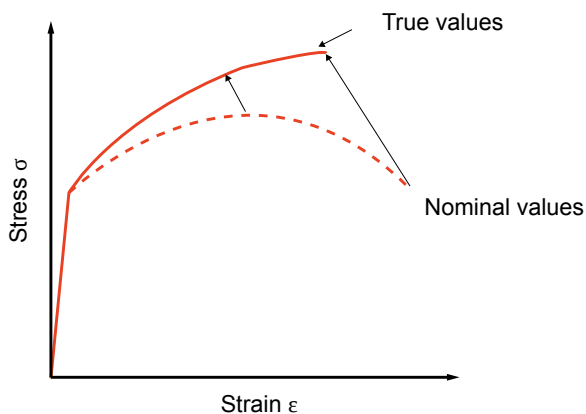
Figure 34. Change from stress-strain curve to true stress-true strain curve.

In order to present stress-strain curves parameterised to analyse work hardening behaviour and deliver input data for computerised analyses, stress-strain curve can be presented by plastic material models, see equations (14)…(17).

$$\sigma = K\varepsilon^n \tag{14}$$

$$\sigma = K_1 (\varepsilon_0 + \varepsilon)^{n_1} \tag{15}$$

$$\sigma = \sigma_0 + K_2\varepsilon^{n_2} \tag{16}$$

$$\sigma = \sigma_1 (1 - Ae^{-B\varepsilon}) \tag{17}$$

All SSAB precision steel tubes pretty well follow equation (14), known as the Hollomon equation, and its parameters also have a physical meaning apart from other material models: k equals stress at 100% elongation and n equals work hardening behaviour.

> **PRO TIP: In most practical cases, it is close enough to assume that SSAB precision steel tubes follow the Hollomon model.**

3.5 Work hardening, n

One way to describe the increased deformation resistance of steel, a.k.a. increased strength, in the function of straining is work hardening, in other words strain hardening or cold working. If we want to determine a work hardening rate for a certain material, let's examine a stress-strain curve e.g. that presented in Figure 34. We know that SSAB's precision steel tubes may follow the Hollomon equation when providing an equation for stress-strain dependency, see Case study 3.9. Because of the nature of the Hollomon equation, a tensile test curve following it will appear as a line when moved to a logarithmic scale, see Figure 35.

Figure 35. Tensile test curve following the Hollomon equation at logarithmic scale. The work hardening exponent corresponds to the gradient of the stress-strain curve.

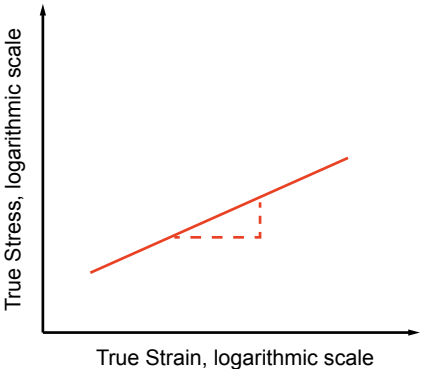A high work hardening capacity, in other words, high n-value, low R_p/R_m ratio or high uniform elongation is generally advantageous in the case of forming processes because of its influence on resisting local necking of the tube wall and is especially important in forming operations under stretching, a.k.a. biaxial straining. Fortunately, pure stretching is quite an unusual state of deformation when manufacturing tubular components. A high work hardening rate is related to higher springback, which may be undesirable behaviour when forming tubes, e.g. with bending.

A close analysis of Docol Tubes which are multi-phase steel grades, shows that normally a more accurate result is gained by calculating two different n-values for different parts of the stress-strain curve. It is characteristic for DP steels to have a double, or even triple, n behaviour, meaning that the work hardening rate will change with increasing elongation.

> **PRO TIP: In most practical cases, it is close enough to assume: $A_g = A_{gt} = n$ = work hardening rate.**

3.6 Strain rate

When evaluating steel structures in dynamic cases, which are high speed movements such as fast forming operations or high-speed structural damage such as car accidents and damage to machinery, it is sometimes worth considering how precision tubes behave. It is known that e.g. IF, structural, HSLA and DP steels have strain rate hardening phenomena, which means that the yield strength and flow stress, a.k.a. stress-strain curve, increase as the strain rate increases.

If we take the Hollomon equation (14) and add the strain rate behaviour component, we get:

$$\sigma = k\varepsilon^n \dot{\varepsilon}^m \tag{18}$$

Where e. is the strain rate and m is constant strain rate exponent. See Figure 36 for the principle of how the stress-strain curve will behave as the strain rate increases.

The Hollomon equation with an added strain rate component is supposedly too simplified a description for many real life applications. This is why more complex equations such as Johnson-Cook (19) are used or the strain rate parameter may be determined simply by linear regression of measured stress-strain curves.
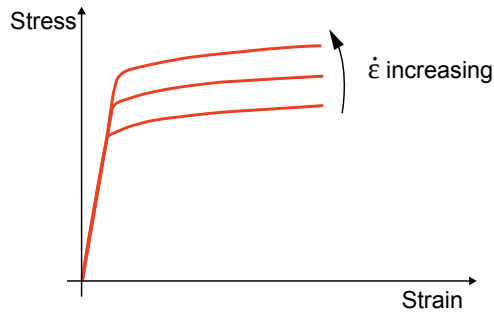
Figure 36. Effect of the strain rate on stress-strain curve.

Johnson-Cook model:

$$\sigma = \left(A + B\varepsilon^n \right)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left(1 - T^{*m}\right) \tag{19}$$

The unit of measurement for the strain rate is 1/s, because it is defined:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{dL}{Ldt} = \frac{v}{L} \tag{20}$$

and

$$\left[\frac{m/s}{m} = \frac{1}{s}\right] \tag{21}$$

The normal strain rate during tensile testing is around 10-3/s (quasi-static). Typical strain rates used in car collision simulations are up to 10^2/s...10^3/s (dynamic). Inside this range, the strain rate dependence of flow stress is explained by thermally activated dislocation motion. For even higher strain rates such as 10^4/s and above, flow stress begins to increase rapidly with strain rate and this is explained by the viscous drag of dislocations. The behaviour of cold-formed steel tubes is quite simple under high strain rates compared to quasi-static conditions of corresponding thin sheet materials. If we know the behaviour of thin sheet material, a.k.a. raw material of the tube, e.g. the strain rate exponent in question, we can measure or evaluate the corresponding tube properties and add the very same thin sheet strain rate effect on stress-strain curve of tube, see Figure 37.

● Tube 220 raw material   ■ SSAB Form 220 Tube
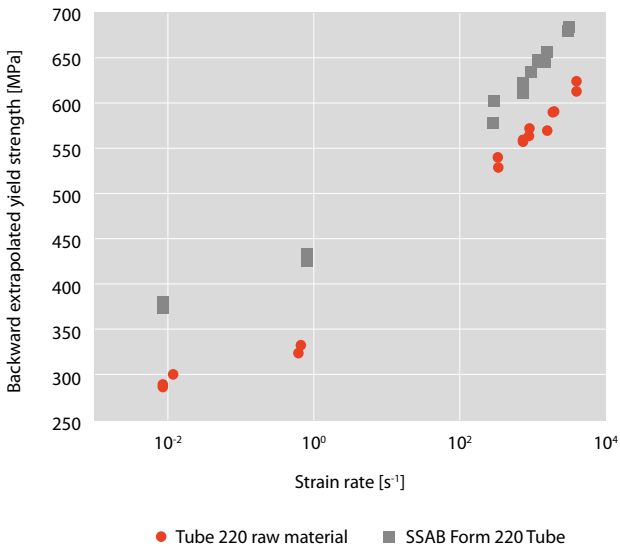
Figure 37. Comparison of the quasi-static and dynamic properties of SSAB Form Tube 220 C raw material and tube.

So, as the high strain rate yield and tensile stresses increase, so, too, do uniform elongation and elongation after fracture. All these together will increase the energy absorption of the material. This can be utilised as an additional safety margin or taken into account in calculations in order to design lighter components potentially subjected to high velocity impact.

PRO TIP: The strain rate depends on the effective length under study.

3.7 Energy absorption

Energy absorption is an important concept of safety systems and assemblies with critical consequences of failure in, for example, machinery, vehicles and yellow goods. A common factor for applications is heavy mass combined with high velocity, giving a high kinetic energy for a moving object. In the case of accident or malfunction, energy absorbers are needed to partially eliminate this kinetic energy in order to protect valuable items, like people, from harmful impact or at least to decrease the kinetic energy to minimise injuries or losses. Hazardous energy may develop from the movement of a protectable object such as a person in a passenger car or an exterior object such as a rock falling from mine roof. Total energy absorption of a structure can be limited e.g. by maximum allowed displacement or development of energy absorption rate as a function of displacement. It is a routine way to design energy absorbing structures so that in minor collisions energy absorbers behave elastically and in major collisions energy absorbers are fully wrecked together with their surroundings.

Thin metal tubes, such as SSAB Form Tubes and Docol Tubes, are recognised as part of an excellent energy absorption structure due to their outstanding load-carrying capability relative to material weight in both axial and lateral loading conditions. A crash incident may include different types of tube behaviour: e.g. elastic beginning, plastic continuation, buckling, local deformation and final failure mechanism. Cross sectional shape, tube dimensions and steel grade properties, together with other structural components and parts, such as tube end stiffeners, are obvious sources for the total behaviour and energy absorption capability of a structure.

Energy absorption is a result of the load-displacement behaviour of a structure. Figure 38 shows the load-displacement curve of Docol Tube 780 45x1.5 in three-point bending setup. In this setup, tube ends are not fixed and energy absorption is the area under the load-displacement curve, see equation (22).

$$[J] = \frac{[kg] \times [m] \times [m]}{[s]^2} = [N] \times [m] \qquad (22)$$
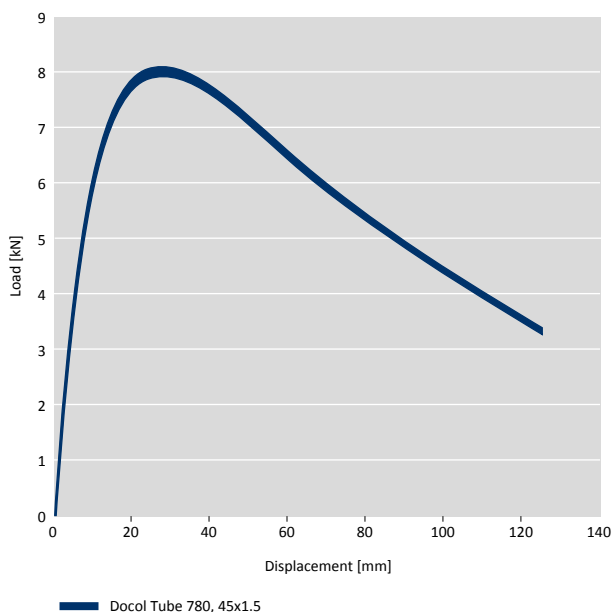
Figure 38. Load-displacement curve in three-point bending.

If two tubes with the same outside dimensions and wall thickness, but different strength level are compared, it is clear that the higher strength steel grade has a higher maximum load carrying capacity. Whereas buckling or collapsing of a tube cross section is a desirable feature of an energy absorbing tube, fracturing is not. When considering all the above-mentioned factors, SSAB Form Tubes and Docol Tubes, with their wide range of dimensions and strength levels, offer vast possibilities to design alternative solutions for energy absorbers.

3.8 Case study: deflection of different tube sizes and material strengths, CE-marking

Typically, precision steel tubes are not used in constructions under design rules. NOTE: SSAB Form tubes, SSAB Boron Tubes and Docol Tubes do not fulfil the requirements of Eurocode design rules. Anyhow, precision steel tubes are commonly used as straight parts or cold-formed designs as load-bearing members in applications, such as furniture, racks and tools, where weight is the primary concern. The safety coefficient is to be determined separately in each case based on the complexity of the structure and the extent of damage resulting from a possible accident.

It is often tempting to choose a steel grade of higher strength and smaller external dimensions or wall thickness for an application. In that case, however, the increased deformations of the structure should be considered, as well as the effect of reduced rigidity on the vibrations of the structure.

Structural requirements are:
1) Stiffness = ability to resist displacement
2) Resistance = strength, ability to carry loads
3) Durability = ability to remain fit for use during the design working life

CE marking of a construction is in a way a passport that entitles the steel construction component or structure to access the installation site where the steel construction will be installed. CE-marking is based on Construction Products Regulation (CPR). EN 10305-3 or EN 10305-5 precision tubes are not generally intended for steel construction use. The letter E (for engineering, e.g. E220) is also used for steel grades. These precision tube norms are not harmonised product norms and do not contain CE-marking requirements (Annex ZA). However, in certain applications it may be possible to use precision tubes in steel constructions, but not in frame applications (load-bearing structure), and even then they must be approved separately. One of the most typical uses of precision tubes is roof safety products.

Example: **Q1)** Calculate based on Figure 39, how many kg a torque arm can support when using 25x10x2 SSAB Form Tube 220 or 30x10x1.25 SSAB Form Tube 320. **Q2)** How many mm will each tube deflect at maximum load?

Let's divide the force F into components F_x and F_y:
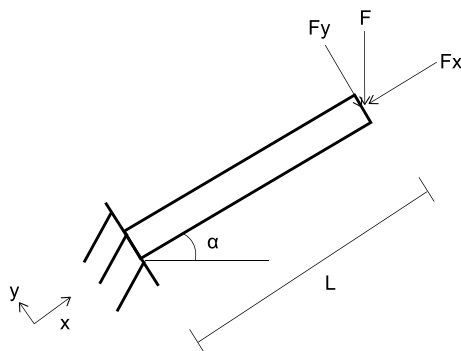
Figure 39. Torque arm loaded with force F and components of F. α = 30° and L = 1100 mm.

Using trigonometry we can create a right angled force triangle:
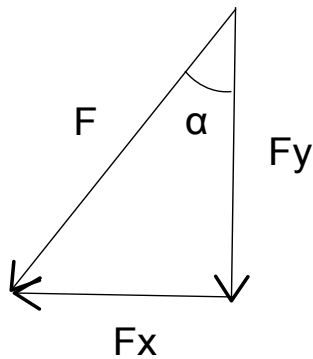
Figure 40. Force triangle for F in Figure 39.

Now it is easy to express F_x and F_y as a function of F:

$$F_x = F * sin\alpha \tag{23}$$

and

$$F_y = F * cos\alpha \tag{24}$$

Table 20. I, Y and W values and area A for the case study tubes. Please check I and W values from Internet page www.ssab.com.

	I [mm⁴]	W [mm³]	E [N/mm²]	A [mm²]
25x10x2 SSAB Form Tube 220	8260.9280	660.8742	210000	123.1416
30x10x1.25 SSAB Form Tube 320	9427.9000	628.5267	210000	93.4147

D/T ratio

$$\pi * D = 2 * H + 2 * B \tag{25}$$

Where: D is the correspondent diameter,
        H is the height of the cross-section and
        B is the width of the cross-section.

$$\frac{D}{T} = \frac{2*H+2*B}{\pi*T} \tag{26}$$

For 25x10x2 SSAB Form Tube 220 we get:

$$\frac{D}{T} \cong 11 \tag{27}$$

And the real yield strength σ_{yield} = 350 N/mm².

For 30x10x1.25 SSAB Form Tube 320 we get: $\tag{28}$

$$\frac{D}{T} \cong 20$$

And the real yield strength σ_{yield} = 460 N/mm².

Tube's strength against yielding

First we need to solve the reaction forces at the stiff support of the tube. Because the support is stiff, reaction forces will occur in the direction of x and y and the reaction moment. Let's write the equilibrium equations at the support:

$$+ \text{x- direction: } R_x - F_x = 0 \leftrightarrow R\_x = F\_x = F * sin\alpha \tag{29}$$

$$+ \text{y -direction: } R_y - F_y = 0 \leftrightarrow R\_y = F\_y = F * cos\alpha \tag{30}$$

$$\text{Moment: } M_{xy} - F_y * L = 0 \leftrightarrow M_{xy} = F_y * L = F * cos\alpha * L \tag{31}$$

Now we can study tube's load carrying capacity. The load carrying capacity depends on how much stress the tube can resist. Usually when the loads are more complex (bending along multiple axes, torsion and bending, etc.) we should take into account normal stresses and shear stresses in multiple directions. Now the bending takes place only along the x-axis so it is enough to check the normal stress along the x-axis.

We want the tube's deformations to stay elastic so the maximum stress limit is the yield strength. The value of normal stress depends on the reaction force parallel to the member and the reaction moment. Maximum stress occurs at the point where the force and moment are at their highest. In this case, the parallel force to the member is constant and the maximum moment reacts at the stiff support. We are now ready to write the equation for normal stress:

$$\sigma_{yield} = -\frac{R_x}{A} + \frac{M_{xy}}{W} = -\frac{F*sin\alpha}{A} + \frac{L*F*cos\alpha}{W} \tag{32}$$

Where   A is the area of tube's cross section,
W is the tube's elastic section modulus and
σ_{yield} is the tube's yield strength.

In the equation force $F*sin\alpha$ is negative because it is compressive in this case. Let's solve the force F from the equation in Newton's:

Tube's strength against buckling

$$F = \frac{\sigma_{yield}}{\frac{L}{W}*cos\alpha - \frac{1}{A}*sin\alpha} \tag{33}$$

If we want to represent force F in kilograms we need to divide the previous equation with the gravitational acceleration g.

$$F = \frac{\sigma_{yield}}{\left(\frac{L}{W}*cos\alpha - \frac{1}{A}*sin\alpha\right)*g} \tag{34}$$

Maximum force F before the tube starts to yield for 25x10x2 SSAB Form Tube 220 is:

$$F = \frac{350 \ N/mm^2}{\frac{1100 \ mm*cos30^0}{660.8742 mm^3} - \frac{sin30^0}{123.1416 \ mm^2}} \cong 243.5 \ N \tag{35}$$

And F in kilograms:

$$F = \frac{243.5}{9.81 \ m/s^2} \cong 24.8 \ kg \tag{36}$$

Maximum force F before the tube starts to yield for 30x10x1.25 SSAB Form Tube 320:

$$F = \frac{460\ N/mm^2}{\frac{1100\ mm*cos30^0}{628.5267mm^3} - \frac{sin30^0}{93.4147\ mm^2}} \cong 304.6\ N \tag{37}$$

And F in kilograms:

$$F = \frac{304.6\ N}{9.81\ m/s^2} \cong 31.0 kg \tag{38}$$

Because the component in x direction of the force F is compressive, we should also take in account the buckling of the member. In this case, we will study the member in the ideal situation so we will assume that the tube is ideally straight and the force Fx affects the centre of tube's cross section. The force when the tube will buckle can be calculated using the following equation, where I is the moment of inertia:

$$P_{buckle} = \frac{\pi^2*E*I}{L_n^2} \tag{39}$$

L_n represents the buckling length of the member which can be found, for example, in textbooks for typical boundary conditions. In this situation, when one end of the member stiff supported and the other end is free, the buckling length L_n is 2*L. Let's substitute L_n with 2*L and write a condition for the maximum load:

$$F_x = F * sin\alpha \leq P_{buckle} = \frac{\pi^2*E*I}{4*L^2} \tag{40}$$

Solving F from the equation we get:

$$F = \frac{\pi^2*E*I}{4*L^2*sin\alpha*g} \qquad \text{In kilograms} \tag{41}$$

You should note that buckling is a stability problem and depends only on the stiffness of the tube (Y, I and L).
Increasing the tube's yield strength won't help.

A1) Let's solve the force F for the case study tubes.
For 25x10x2 SSAB Form Tube 220 we get:

$$F = \frac{\pi^2*210000\frac{N}{mm^2}*8260.928\ mm^4}{4*(1100mm)^2*sin30^0*9.81\ m/s^2} \cong 720\ kg \tag{42}$$

And for 30x10x1.25 SSAB Form Tube 320 we get:

$$F = \frac{\pi^2*210000\frac{N}{mm^2}*9427.9\ mm^4}{4*(1100mm)^2*sin30^0*9.81\ m/s^2} \cong 823\ kg \tag{43}$$

You can see that in this case buckling wouldn't occur because with forces like these the tube would have yielded already.

Tube's maximum deflection

To find the member's maximum deflection, we need to solve its deflection curve. There are basically two ways to do this. We can generate a mathematical representation from the member using boundary conditions or we can get the deflection curve from "beam tables", which are a collection of formulas for some simple boundary conditions and load situations. These "beam tables" can be found in textbooks, for example. Beam tables will usually include the formula for the deflection curve and for the maximum deflection. In this case, where we have a concentrated force acting at the free end of the tube and the other end is stiff supported, the easiest way is to use the beam tables. Maximum deflection δ occurs at the free end of the member:

$$\delta = \frac{P*L^3}{3*E*I} \tag{44}$$

Let's substitute P with Fy = F*cosα and we get:

$$\delta = \frac{F*cos\alpha*L^3}{3*E*I} \qquad \text{in millimeters in the negative y-direction} \tag{45}$$

The deflection depends only on the rigidity of the tube so if you want to decrease deflections, you should choose a tube with a larger cross-section.

A2) For 25x10x2 SSAB Form Tube 220 the maximum deflection would be:

$$\delta = \frac{243.5\ N*cos30^0*(1100mm)^3}{3*210000\frac{N}{mm^2}*8260.928\ mm^4} \cong 54\ mm \tag{46}$$

$$\delta = \frac{304.5\ N*cos30^0*(1100mm)^3}{3*210000\frac{N}{mm^2}*9427.9\ mm^4} \cong 59\ mm \tag{47}$$

PRO TIP: Precision steel tubes have an excellent ratio between own-weight and stiffness and resistance, since the closed cross-sectional shape, wall thickness and steel grade can be almost freely defined for each application.

Figure 41. Snow guards manufactured from SSAB Form precision steel tubes.

3.9 Case study: evaluating true stress – true strain curve

True stress – a true strain curve may come in handy, e.g. in Finite Element Modelling, where it is used as starting data. Much simulating software contains a product or material library; the user defines the material used and the software searches and applies the mechanical properties automatically. Sometimes this is enough, but sometimes it is worth evaluating the effect of natural deviations in the material properties or the modeller may want to simulate the behaviour of a precision steel tube which does not exist and has therefore never been tensile tested.

Let's construct a true stress – strain curve for a 50x1.5 SSAB Form Tube 220. The D/T ratio for the tube is 33.3. SSAB's technical customer service can provide a tensile test curve for SSAB Form Tube 220 with D/T = 33.3, which is shown in Figure 42. Note that we are now aiming a rough estimation for material selection purposes and want to use a typical tensile test curve. Depending on fabrication technology and final application, this may not be the wisest choice. Actually, it would be a good idea to know a little bit more about the real variables of factors such as yield strength and work hardening exponent in order to be on the safe side.
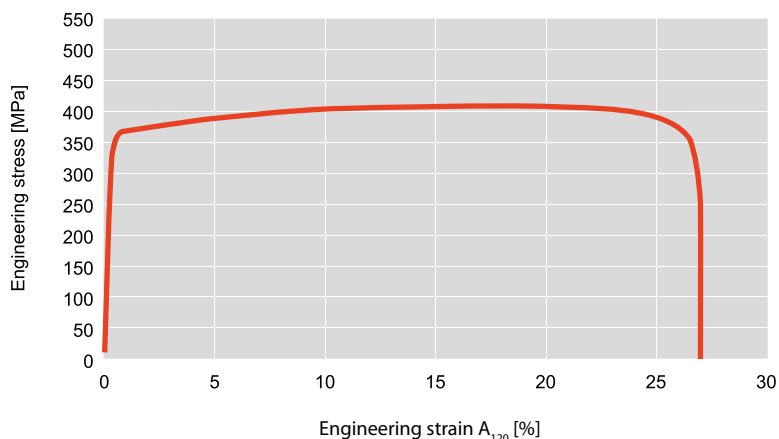
Figure 42. Tensile test curve for SSAB Form Tube 220 with D/T = 33.3.

Engineering stress is the stress which is calculated on the original cross sectional area of the test piece. It means that the necking of the cross section during extension is neglected. Engineering strain is the ratio between the elongation and the original length of the test piece. A_{120} in Figure 42 shows that the length of the parallel portion of the test piece at the start of the test is 120 mm.

In the tensile test, deformation of the test piece takes place incrementally because the tensile force increases gradually. Generally, we can use the true strain to take into account the influence of the strain path or calculate summation of strains.

The true strain consists of several incremental strains ∂e:

$$\partial e = \frac{\partial L}{L} \qquad (48)$$

By integrating these incremental strains, we can find the relationship between the true strain ε and the nominal strain (engineering strain) e:

$$\varepsilon = \int_{L_0}^{L_u} \frac{\partial L}{L} = \ln\frac{L_u}{L_0} = \ln(1 + e) \qquad (49)$$

where ε is the true strain,

e is the nominal strain (engineering strain),

L_0 is the original gauge length and

L_u is the final gauge length after rupture/fracture.

During extension, the cross sectional area of the test piece gets smaller. When talking about true stress we take into account the impact of the shrunken cross section on the stress. The relationship between the true stress and the nominal stress (engineering stress) can be expressed as follows:

$$\sigma = R * (1 + e) \qquad (50)$$

Where σ is the true stress and

R is the nominal stress (engineering stress)

Now, by applying the values of the tensile test curve, see Figure 42, to the equations shown above and by taking logarithm to base 10 from the values obtained we get the following true stress - strain curve:
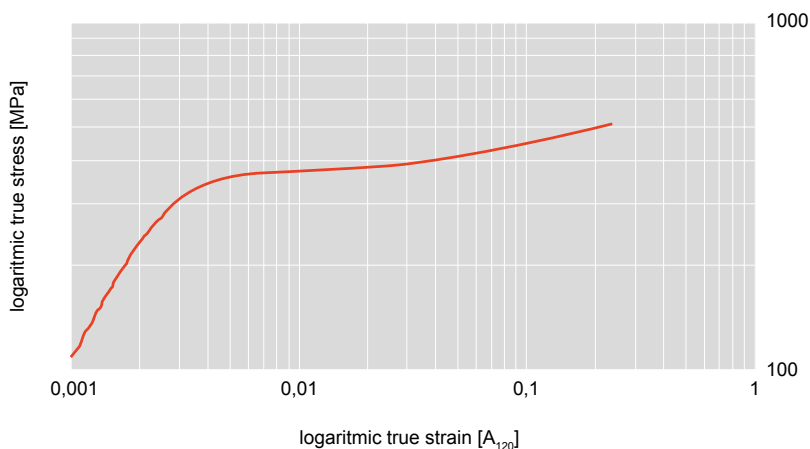
Figure 43. True stress - strain curve in logarithmic scale. Adapted from Figure 41.

In logarithmic scale, the Hollomon equation (14) gives a straight line where the value n is the line's slope. If we now consider that the curve in Figure 43 consists of two lines, we neglect the beginning of the curve due to inaccuracy in the testing arrangement, and we solve the slope of the last line (the line that starts at point true strain = 0.03). This gives the value n in Hollomon's equation. We need to solve also the parameter K in Hollomon's equation. Let's extrapolate the values of the last line to get the value of true stress when the true strain is 1. The parameter K is the value of true stress at that point.

Finally, we will use the Hollomon equation to draw a curve in a normal coordinate system with the solved values of n and K. Also we need to correct the value of Young's modulus because the tensile test doesn't normally give the right value for it. Young's modulus for steel is 210GPa. These procedures give a true stress - strain curve as shown in Figure 44.
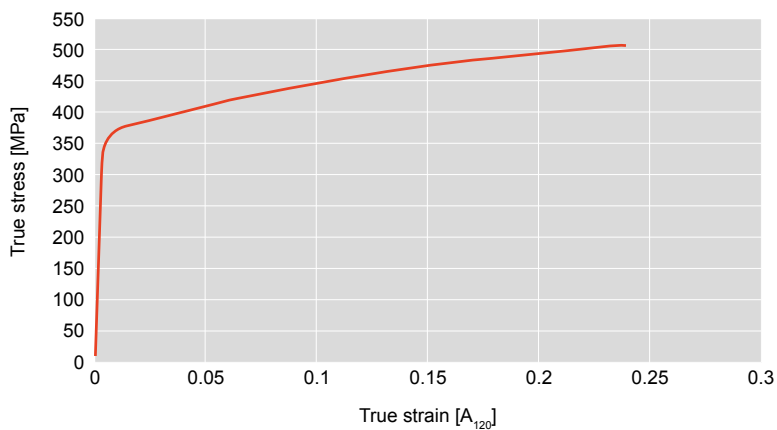
Figure 44. True stress - true strain curve with corrected Young's modulus.

PRO TIP: SSAB Form Tubes from 190 up to 420 follow the Hollomon equation. This is true also for higher-strength steel grades, but double or triple "n" behaviour may occur.

4. Tube bending

Bending is the second most common processing method for precision tubes after cutting. A total of 40-50% of precision tubes delivered are bent. Bending is more common than, for example, painting or welding. In order to ensure good quality and reasonable manufacturing costs, it helps to be familiar with some of the typical properties of precision steel tubes and basic bending principles when designing a product for bending. For basic bending terminology, see Figure 45.
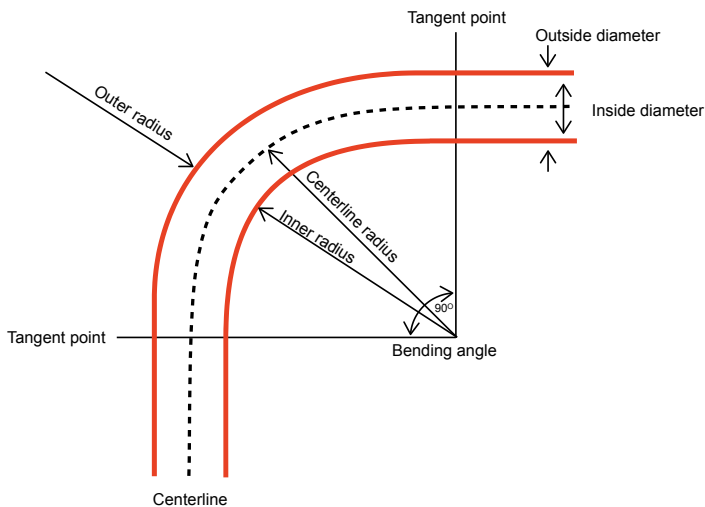
Figure 45. Bending terminology.

Tube bending may be carried out using many different methods and tooling setups. Special tube bending machines are long-term investments and their service life can be up to decades, particularly when numerous different tools are available and can be updated based on new products in production. Hydraulic bending machines are traditional, but fully electric bending machines are also available now.

Figure 46. Kaari coat racks with bent rectangular SSAB Form Tube 220 C 40x10x2. Courtesy of Martela Oyj.

4.1 Neutral axis and springback

During the bending process, there is an area around the neutral axis where the stress does not exceed the yield strength of the material and, therefore, this area is elastic. Also, when deformation takes place during the bending process, a lot of residual stresses are introduced and after the bending tooling is removed and stresses released, the tube part exceeding the yield strength tends to return to its former shape according to the modulus of elasticity, see Figure 47. This is called springback.
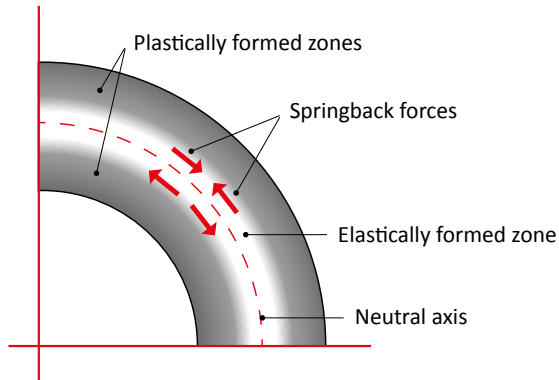
Figure 47. Plastically and elastically formed areas in bending.

Because of springback, components may be out of tolerances at the other end of a bent tube and it is almost impossible to bend a tube by only a few degrees. When there are several bends next to each other, form defect caused by springback is multiplied, see Case study 4.1.1 Springback can also be seen as an increased bending radius, see Figure 48.
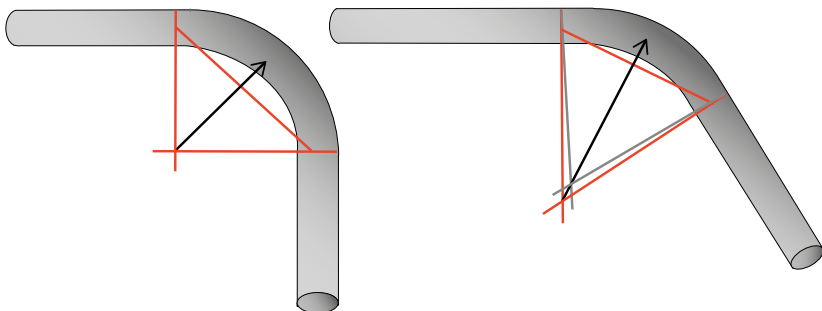
Figure 48. Increasing bending radius originating from springback.

Material parameters having the strongest influence on springback are:
- Young's modulus
- Yield strength
- Tensile strength
- Work hardening rate

Within the precision steel tube product group, Young's modulus is pretty much constant and cannot be varied based on experiences of the bending process. Also yield and tensile strength are typically selected on a basis other than springback behaviour. The work hardening rate may be described by the R_p/R_m ratio, uniform elongation or work hardening exponent, which are steel grade and tube manufacturer dependent parameters. Thus, the most practical way to tackle springback is to compensate it by fabrication process adjustments and taking care of tooling maintenance.

In some cases, springback may be limited by increasing stretching during deformation, which is generally difficult to carry out when bending a tube, or using structural features, a.k.a. stiffeners, in order to constrict the release of residual or elastic stresses with part geometry, which may give the part an undesired appearance.

Since springback is related to the elastic behaviour of the tube, variation in yield strength between e.g. different production batches also causes variation in the amount of springback. A rule of thumb is that a variation of ±10MPa in yield strength causes a variation of approximately ±0.1° in the bending radius. In addition, an HF-weld which is harder and stronger than the base material causes a maximum of approximately ±0.1° variation in bending radius.

Normally, when forming steel, it is important to try and achieve evenly-distributed plasticity. In the case of tubular bending, it is impossible to distribute plasticity evenly e.g. between the outer and inner radius. The higher the tube strength, the greater the springback. There are two reasons for this: with higher-strength steels, the variation in yield strength tends to be higher, as is the elastic recovery when releasing tube from tooling, see Figure 49. If two tubes with the same dimensions but different yield stresses (steel grades or delivery batches) are bent to the same radius, i.e. to the same elongation, the elongations reached must be different before tooling release.
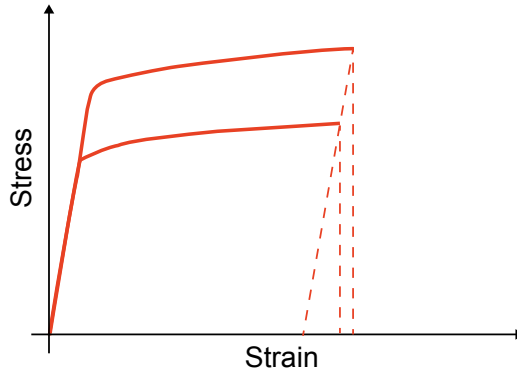
Figure 49. Elastic return of two different tube materials after tool releasing by way of stress-strain curve.

When the variation, inter alia, in the positioning accuracy, tooling clearances of a standard bending machine and clearance between mandrel and tube are taken into account, the machine and process induced variation in the bending radius can be estimated to be approximately ±0.5°.

4.1.1 Case study: Springback and component tolerance

Examination of four consecutive bends in a 1000 mm long HF-welded tube, see Figure 50, shows that, in theory, the position of the end of the tube may vary by as much as ±24 mm:

If the following is assumed:
- Yield strength deviation of the tube is ±35MPa
- Tube is HF-welded
- Bending tooling and clearances are as usual

Then bending angle deviation due to:

- Yield strength is ±0.35°
- HF-weld is ±0.10°. This is for low-alloyed Form and Docol precision steel tubes. Alloyed steels may have different behaviour because of weld hardening.
- Bending tooling and clearances is ±0.50°

And the total deviation will be:

$$\sqrt{\pm0.45°^2\pm0.45°^2\pm0.45°^2\pm0.45°^2\pm0.50°^2\pm0.50°^2\pm0.50°^2\pm0.50°^2} = \pm1.35° \quad (51)$$

And for 1000mm length ±1.35° variation means:

$$x = tan \pm 1.35 * 1000mm = \pm24mm \quad (52)$$
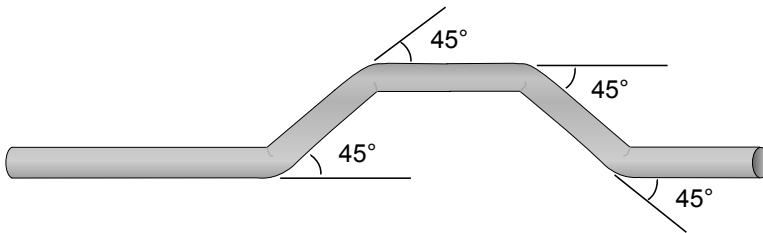
Figure 50. Four 45° bends in the same component.

> **PRO TIP: Do not mix different bundles in production, because keeping tubes from the same batch together will keep yield strength deviation under control. This is also valid when fixed cut tubes are used. The same applies to bundles from different tube suppliers.**

4.2 Bending methods and applicable radii

A tube must not break when bent, in addition to which requirements are set for buckling and wrinkling, depending on the application of the component. The thinner the tube wall and the smaller the intended bending radius, the easier the wall becomes wrinkled and the more the bending tools must support the tube wall.

The minimum centreline bending radius, which is achieved using well-serviced tools and the normal rotary draw bending method, see Chapter 4.2.4, can be shown as an empirical formula:

$$CLR = 50 \times \frac{D}{A} \qquad\qquad (53)$$

Where: CLR is centreline radius
D is tube diameter and
A is elongation percentage

The formula illustrates that a bending radius of 1xD requires an approximately 50% elongation of the material. Respectively, an elongation of 23% enables the bending of a 25mm tube using a radius of 54mm.

The equation is for guidance only and the radius achieved greatly depends on the bending technique used and on the operator's skills. In draw bending, the bend radius derived from the equation (53) has been achieved with elongation values lower by more than five percentage points.

Table 21. Minimum mechanical properties for SSAB Form Tubes and tubes according to standard EN 10305.

Steel grade	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]
E190+CR2	190	270	26
SSAB Form Tube 190	190	270	35
E220+CR2	220	310	23
SSAB Form Tube 220	220	310	28
E320+CR2	320	410	19
SSAB Form Tube 320	320	410	23
E420+CR2	420	490	12
SSAB Form Tube 420	420	490	14

As explained in chapter 3.1, all tubes of a similar steel grade are not similar but have different mechanical properties depending on their dimensions. When combining elongation values and the D/T relationship from Figure 51 with the formula (53), a minimum bending radius can be shown as a function of D/T, see Figure 52.
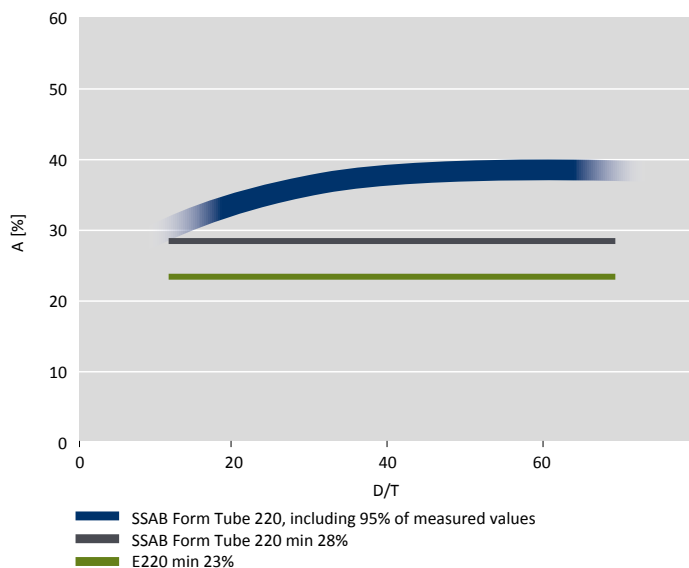
Figure 51. Elongation values A for steel grade SSAB Form Tube 220. Average bending radii have been calculated using 95% of the relevant products' A values.
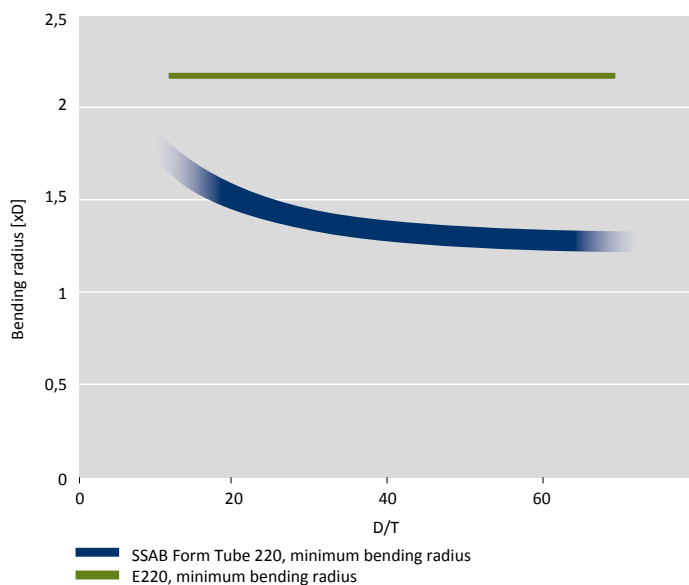
Figure 52. Minimum bending radius of SSAB Form Tube 220 vs. tube D/T ratio. Based on Figure 51 with 95% criterion.

Table 24 shows the indicative minimum bending radii and the most common bending defects with these radii when using an E220 CR2 tube with a D/T ≈ 30 complying with standard EN 10305-3.

Table 22. Comparison between SSAB Form tubes and the elongations specified in EN 10305; delivery condition: +CR2. Average bending radii have been calculated using 95% of the relevant products' A values.

Steel grade	A min. [%]	CLR min.	A [95%] D/T = 15	CLR [95%] D/T = 15	A [95%] D/T = 50	CLR [95%] D/T = 50
E220 EN 10305	23	2.2xD	–	–	–	
E320 EN 10305	19	2.6xD	–	–	–	
SSAB Form Tube 220	28	1.8xD	30	1.7xD	38	1.3xD
SSAB Form Tube 320	23	2.2xD	25	2.0xD	33	1.5xD

If a very small bending radius with respect to the material is used, the HF-weld of the tube should be positioned on the neutral axis of the bend. Positioning the HF-weld on the inner surface can decrease wrinkling tendency.

The bending radius of a component can be reduced by compressing the tube wall inside the tube like a pocket, see Figure 53. This compression is easiest to fabricate with pressing. Then, if applying Formula (53) into this pocket bending, a new smallest cross section diameter can be used, e.g. when the compressed pocket is wall to wall, the tube diameter is halved. Pocket bending can thus potentially halve the minimum bending radius.

Figure 53. Decreasing bending radius by decreasing "D" of the tube.

Bending square and rectangular tubes differs a bit from bending circular tubes. Work-hardened corners tend to increase minimum bending radius and the tube is more exposed to cross section changes: outer and inner surfaces have a tendency to concave, sides have a tendency to convex. Pocket bending is a common way to bend angular tubes, but they can also be bent without. Using draw bending, high quality tooling, ball mandrel and increased bending radius, it is possible to reach a bending radius down to 3 x tube height (3xD) with only a small cross sectional deformation, see Figure 54.

Figure 54. Bending square and rectangular sections.

PRO TIP: Check your tube's elongation at fracture (A%), then select bending radius!

4.2.1 Roll bending

Figure 55 shows the principle of roll bending. Roll bending, which does not require many tools and is therefore an inexpensive investment, is based on the use of three rolls, which form a supporting point triangle between which there is no support for the tube. Compared to other bending methods, longer straight sections must be left at both ends of the tube in roll bending. This means that bending cannot be carried out too close to the end of the tube or tube end must be cut.

In roll bending, three-point bending and compression bending, the neutral axis moves away from the centreline towards the outer surface. For this reason, outer surface tension is smaller than inner surface compression and tubes are susceptible to buckling when using these methods and therefore, when combined with a small bending radius, there is a risk of the tube collapsing. Therefore, the achievable minimum bending radius is larger than with many other methods.
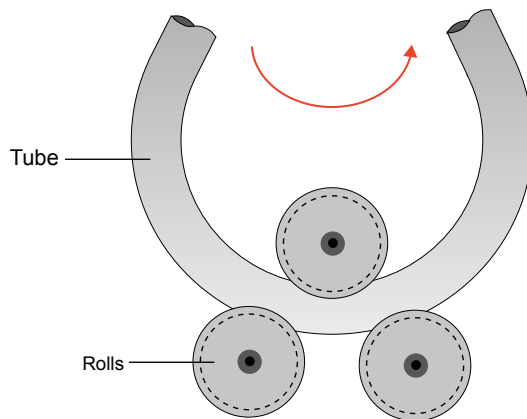
Figure 55. Roll bending, the easiest way to produce over 180° tube spirals e.g. for heat exchanger applications.
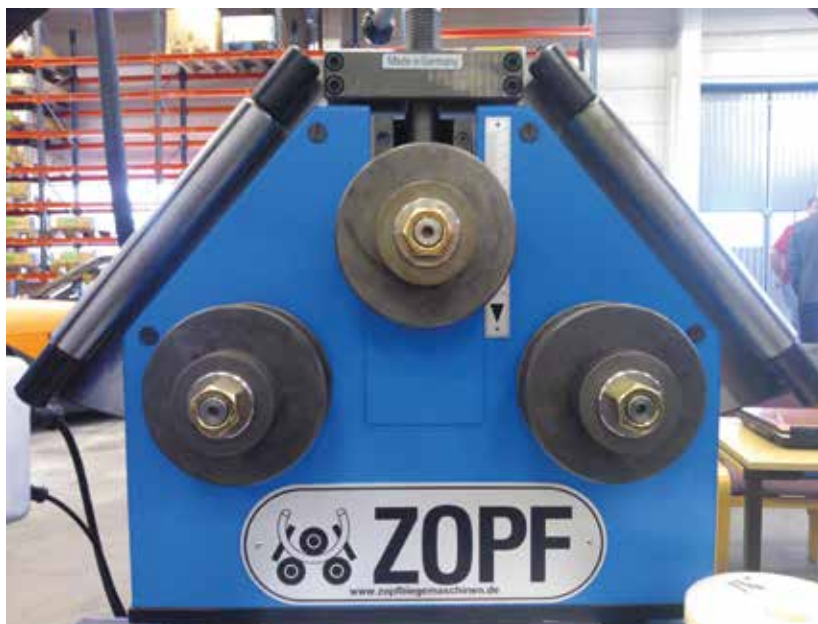
Figure 56. Roll bender. Courtesy of Herber Engineering AB.

4.2.2 Push bending – three-point bending

One of the most simplified bending methods and thus having the lowest investment costs, is push bending, which is also known as:

- Press bending
- Ram bending
- American bending
- Three-point bending

Figure 57 shows the principle of three-point bending. As with roll bending, there is no support for the tube between the supporting points. In addition, a tube with small uniform elongation tends to become detached from the surface of the ram/bending die, which causes buckling of the tube, see Figure 58. The probability of detaching greatly increases when elongation on the tube's outer surface exceeds uniform elongation. This usually occurs when CLR = 5xD. Detaching may be prevented by counter force tooling pressing the tube towards the bending die.

The possibility to set up push bending tooling on a regular eccentric or hydraulic press is a major advantage. This may be considered especially when:

- A large bending radius is applicable
- Bending defects, like wrinkling, are allowed, e.g. the bent part will not be visible in design
- High volume items are manufactured at high production rates
- Minimum tooling investment is required, such as with small series and prototyping

When manufacturing a single part, such as in the prototyping phase, moistened and compressed sand or another tube inside may be used as a disposable mandrel if low costs are pursued before investing in e.g. draw bending tooling.
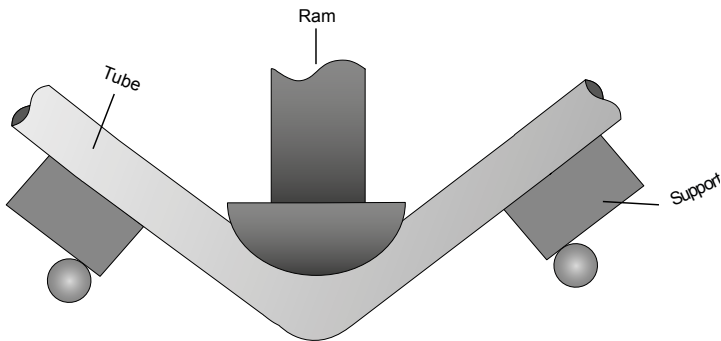
Figure 57. Push bending.
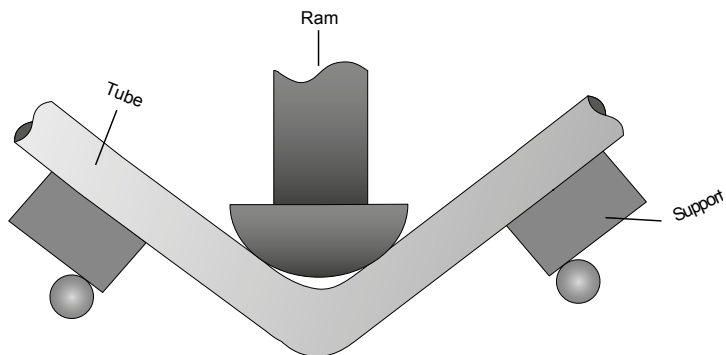
Figure 58. Losing contact between the tube surface and tooling because uniform elongation of the material is exceeded.

One major application for three-point bending is to evaluate the energy absorption of the tube, e.g. in the case of safety components. Several factors, such as tube dimensions, aka cross-sectional properties and steel strength, affect energy absorption capability, which coincide with the total area under the load-displacement curve, see Figure 59. A closed tube cross section will give a much higher bending resistance compared to open profiles.
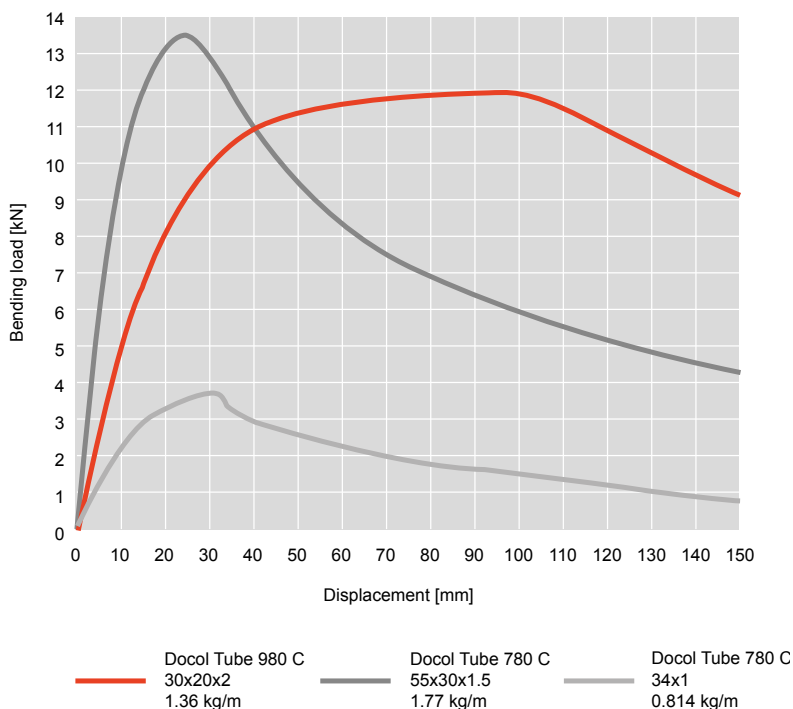
Figure 59. Load-displacement curve adapted from a 3-point bending test showing energy absorption behaviour.

4.2.3 Compression bending

In compression bending, see Figure 60, the tube is pressed, i.e. bent, around a stationary bending die. Compared to the previous methods, the tube is better supported by the tooling albeit without precision. In any case, the tube is not supported from the inside by the mandrel, causing thin walled tubes to wrinkle, collapse or to assume an excessive oval-shape.
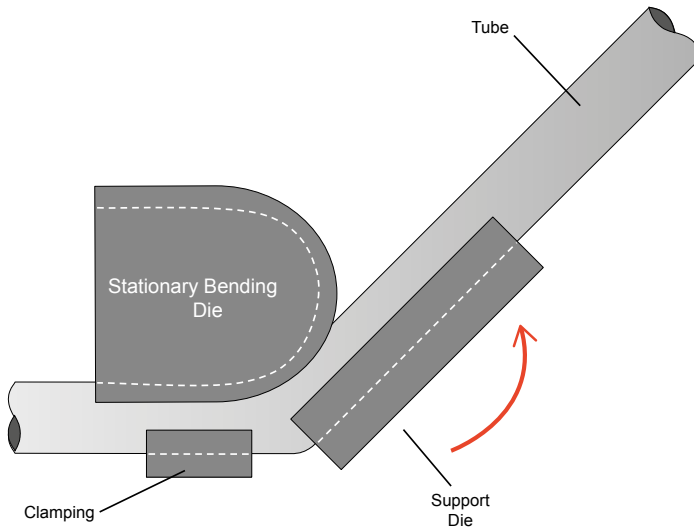
Figure 60. Compression bending

Compression bending could be a good compromise between push and draw bending with regard to bending quality (wrinkling, ovality, necking, wall thinning) and the achievable bending radius. Anyhow, compression bending is not very common and sales of new machines are low.
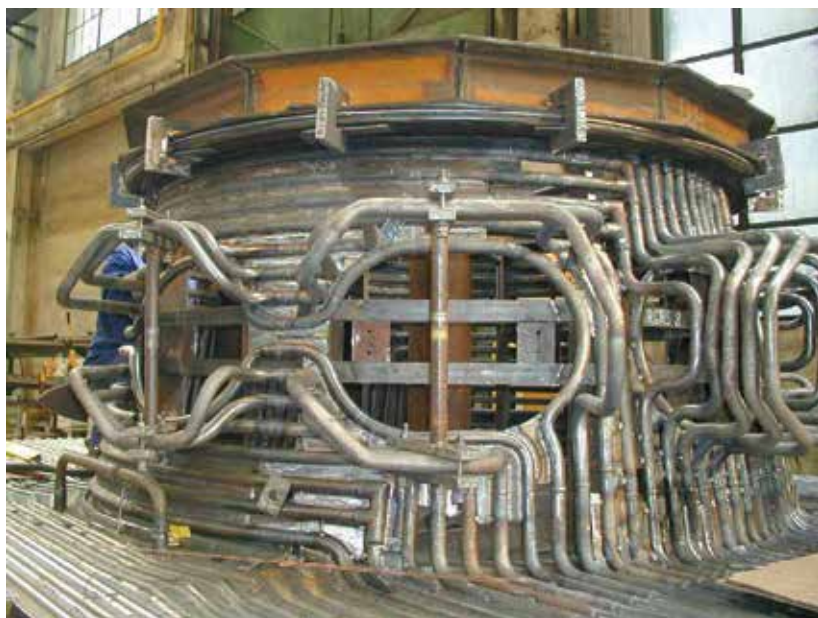
Figure 61. Boiler tubes. Depending on the bending radius required and wall thinning allowed, several different bending methods may be used: from compression bending to clamping booster bending.

4.2.4 Draw bending

Figure 62 illustrates the principle of rotary draw bending, shorter draw bending or mandrel bending. In rotary draw bending, the tube is drawn over a rotating bending die, Figure 62. In this method, the neutral axis is closer to the inner than to the outer surface of the bend, which allows wrinkling control. A mandrel which supports the tube from the inside can also be used in rotary draw bending.

Draw bending allows smaller bending radii at higher D/T ratios than other methods. As a rule, bending is carried out using a mandrel, see section 4.3 for mandrel usage. High tube wall support with tooling, such as the wiper die shown in Figure 63, is also advantageous when requiring a minor oval shape for products. The weaknesses of this method compared to push bending include higher machine and tooling costs, a greater reduction in wall thickness on the outer side of the tube bend and the unbent section left at the tube and by the clamp jaws. Clamping length is usually 2...3xD. When the bending machine's plane selection for the linear transfer and rotation of the tube is used instead of manual positioning, an unbent section might be left at the back end of the tube only, depending on the bending radius. Three dimensional

parts can be easily bent using draw bending, either by manually rotating the tube between bends or by using an automated system, see Figure 64. When aiming for minimal bending radius or placing an HF-weld of the tube in a certain position for part similarity, an automated weld seam detector may be used.
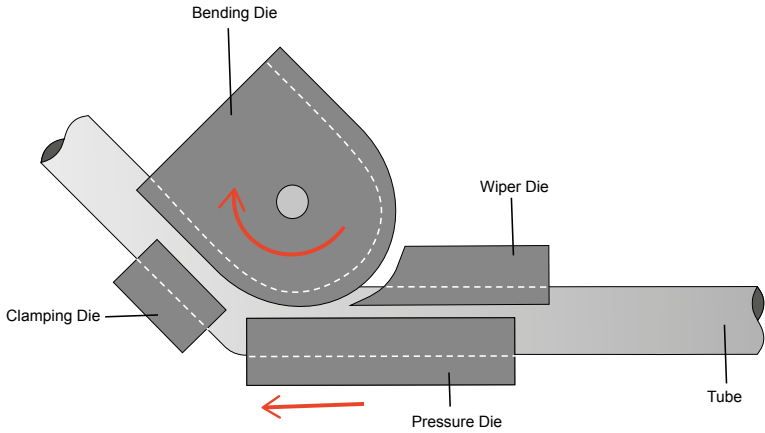
Figure 62. Draw bending.
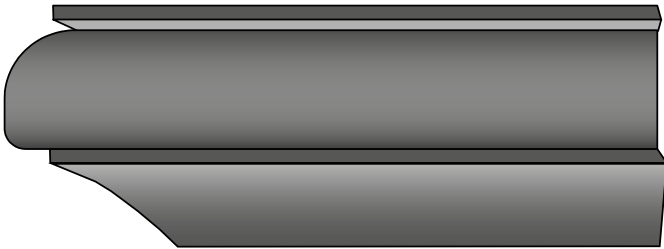
Figure 63. Wiper die usually made of softer material than the tube, e.g. aluminium-bronze.

Figure 64. 3D bending with automated rotation. Courtesy of Herber Engineering AB.

Figure 65 shows the booster bending method and it can be easily noticed that it is a special modification of draw bending: obviously most of the tooling is similar to it. In this method, a booster force pushes the tube to the bending area. The booster force compensates for the tensile elongation and wall thinning on the outer surface of the tube by adding a compressive elongation, which then allows smaller bending radii to be used than with traditional rotary draw bending. Tube wrinkling tendency would be increased without precision tooling such as the wiper die setup.
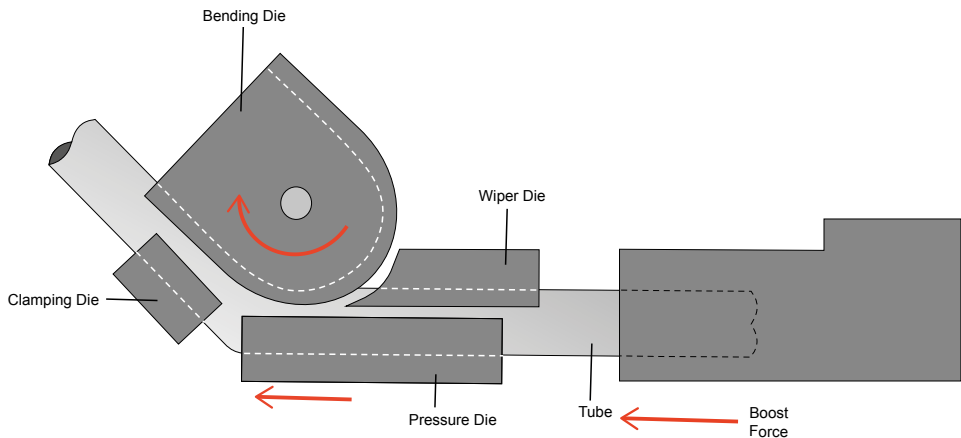
Figure 65. Booster bending.

Another tooling setup exploiting the booster force idea is clamping booster bending or centreline booster bending, see Figure 66. In clamping booster bending, the booster force is exerted on the tube by clamping tooling. The method is typical for pressure vessel and heat exchanger applications because of their generally thicker tube walls, which may make it unnecessary to use the wiper die and mandrel.
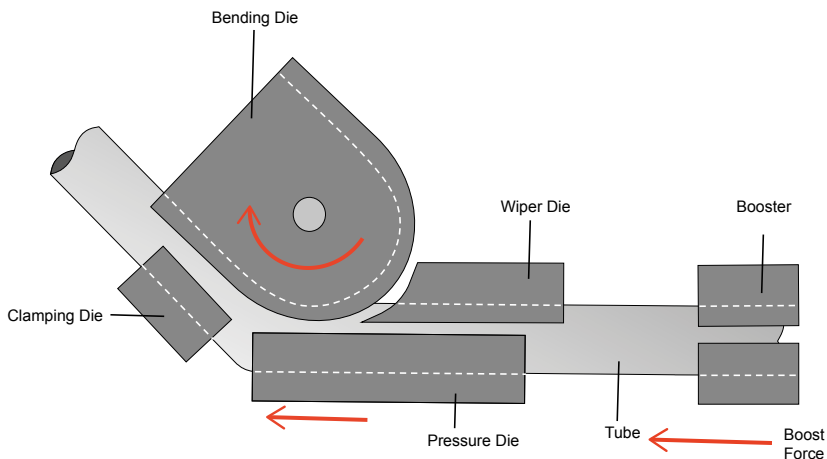
Figure 66. Clamping booster bending, here with a wiper die.

The booster force does not have to be constant, but it can be adjusted during bending action, e.g. at the start of bending some extra force may be exerted on the tube to optimise wall thickness.

4.2.5 Free radius bending

Free radius bending is also a kind of rotary draw bending variant with the exception that the clamping die does not rotate in a fixed position in relation to the bending die but has been replaced with an independently controlled bending die roll. This independent control makes it possible to change or adjust bending radius during and within one bend. The bend may be a so-called changing radius bend. This method gives new freedom to design parts with even less welding than other bending methods.
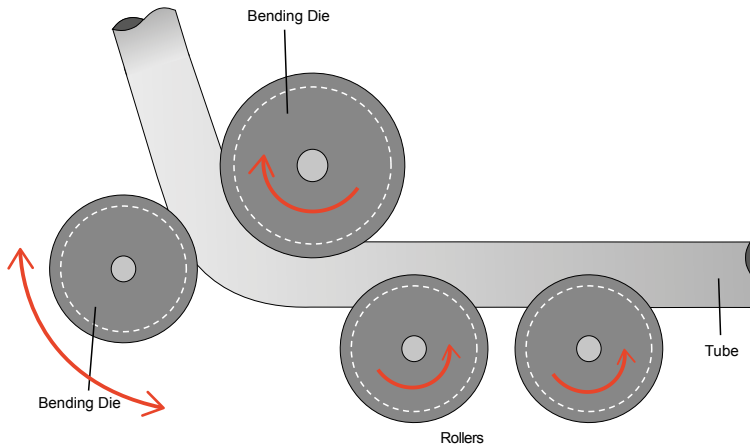
Figure 67. Free radius bending.
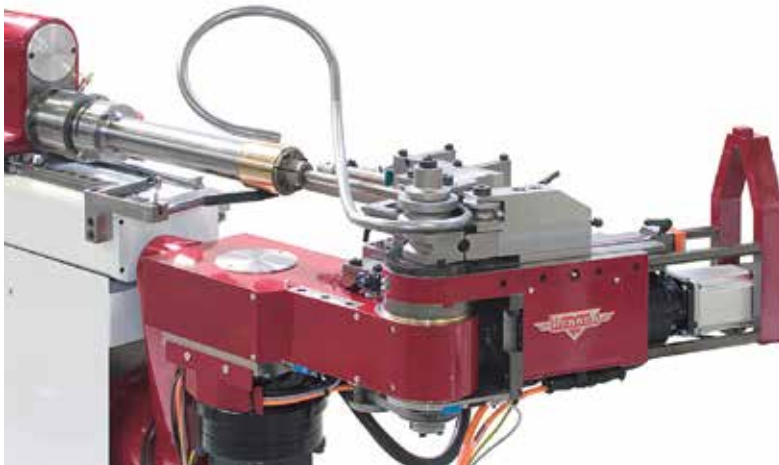
Figure 68. Free radius bending machine. Courtesy of Herber Engineering AB.

4.3 Mandrels

If, due to the large D/T ratio, even rotary draw bending does not sufficiently support the tube wall against wrinkling, a mandrel can be used inside the tube during bending. The simplest type of mandrel is a plug mandrel that, together with other tools, supports the wall up to the tangent point of the bend, see Figure 69. The wall can be supported past the tangent point using a rounded spoon mandrel. When bending a tube with very thin walls or small bending radius, the tube needs to be supported over a longer bent area. This can be done using a ball mandrel, Figure 69.

A common method for mandrel adjustment is to place the mandrel so far forward, i.e., over the tangent point that the tube is close to the breaking point and then move the mandrel slightly backwards. This is how to find an optimal mandrel position in which the tube does not break and the mandrel gives maximum support to the tube wall. A typical mandrel position is 0.4 mm forward, see Figure 70.
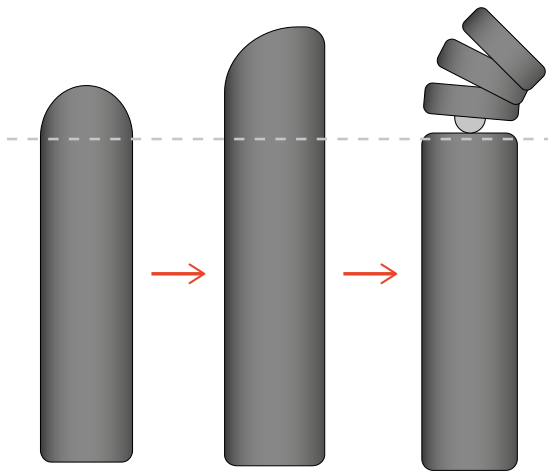
Figure 67. Mandrels. From the left: a plug mandrel, a spoon mandrel and a ball mandrel.

Figure 70. Mandrel positioning. Left: the mandrel is in a tangent point location. Right: the mandrel is in a forward location reducing wrinkling tendency and causing some extra deformation of the outer tube wall.

Figure 71 shows a nomogram for selection of the correct mandrel type. The left hand side of the nomogram indicates whether a mandrel is needed or not and the type of the mandrel to be used. The right hand side indicates the number of balls if a multi-ball mandrel is needed.

Figure 71. Nomogram of the use of a mandrel.

Another approach to mandrel usage is to use Table 23, where also the bending angle is considered.

Table 23. Guide to select the correct mandrel for draw bending and booster bending. Please note that this table does not take the applicable minimum bending radius into consideration.

CLR/Tube diameter	1XD		1.5XD		2XD		2.5XD		3XD		5XD	
Bending Angle	90°	180°	90°	180°	90°	180°	90°	180°	90°	180°	90°	180°
D/T												
10	P	P	P	P	P	P	P	P	N	P	N	N
20	MB1	MB1	MB1	MB1	MB1	MB1	P	P	P	P	P	P
30	MB2	MB3	MB2	MB3	MB2	MB3	MB1	MB2	MB1	MB2	P	P
40	MB3	MB3	MB3	MB3	MB3	MB3	MB3	MB3	MB2	MB3	P	MB1
50	MB3	MB4	MB3	MB4	MB3	MB4	MB3	MB4	MB3	MB3	MB1	MB2
60	MB4	MB5	MB4	MB5	MB3	MB4	MB3	MB4	MB3	MB4	MB3	MB3
70	MB4	MB5	MB4	MB5	MB3	MB4	MB3	MB4	MB3	MB4	MB3	MB3
80	MB4	MB5	MB4	MB5	MB3	MB4	MB3	MB4	MB3	MB4	MB4	MB4

N= No mandrel
P= Plug mandrel
B= Bal mandrel
MB= Multi-Ball mandrel, number indicates the recommended number of balls
A wiper die is recommended when the proportion outside the D/T-ratio is within the grey field

In demanding bending processes, the clearance between the tube and the mandrel must not exceed 0.15 mm. For this reason, mandrels with various diameters should be available for the bending of tubes from different production batches, taking into account their manufacturing tolerance. If tubes are supplied without scarfing of the inner seam of an HF-weld, the clearance increases due to bead. In this case, a machined groove in the mandrel can be used.

It is always a good idea to consider the placement of the weld seam during bending. If a bending radius close to the minimum is used, the weld should be placed near the neutral axis of the bend in order to decrease elongation on the weld. If the bend has a tendency to wrinkle, placing the weld on inner radius location might help.

Like wiper dies, mandrels are usually made of a notably different material than the tube, such as aluminium-bronze or hard chromium steel, not just in order to avoid part scratching but primarily also to avoid adhesive corrosion between the tube material and tooling.

If a mandrel and wiper die must be used in bending, also a lubricant must usually be used. Lubricants have developed since the early days of grease, oil

and soap to petroleum-based special lubricants, synthetic non-petroleum and further to environmentally-friendly water-based and gel lubricants. Beside environmental friendliness, modern lubricants are easy to clean off even with water. The latest gel lubricants will even dry on the tube surface without the need for washing.

> **PRO TIP: A hot-rolled pickled (H) surface will wear out mandrels and wiper dies faster than a cold-rolled (C) surface.**

> **PRO TIP: Inhomogeneity of the weld seam may prevent wrinkling. Try to locate the weld seam in the inner bend if wrinkling is a problem.**

4.4 Case study: bending angle in plane

When comparing middle line lengths and outer surface lengths and then calculating the inevitable elongation occurring at 90° and 180° bends, we can see that elongation of the outer surface does not depend on the bending angle, see Figure 72. Thus, as regards tube fracture, a large bending radius is no more difficult than a small bending radius. The secret is that in draw bending, the tube elongates at the tangent point of the bend, then moves ahead and the next part of the tube will transfer to the tangent point and elongate, etc.

—— ¼ circle
length of line = $2\pi(r+D/2)/4$ = 180,55mm

— — · ¼ circle
length of line = $2\pi r /4$ = 157mm

Elongation = (180,55mm-157mm)/157mm = 15%

—— ½ circle
length of line = $2\pi(r+D/2)/2$ = 361,1mm

— — · ½ circle
length of line = $2\pi r /2$ = 314mm

Elongation = (361mm-314mm)/314mm = 15%
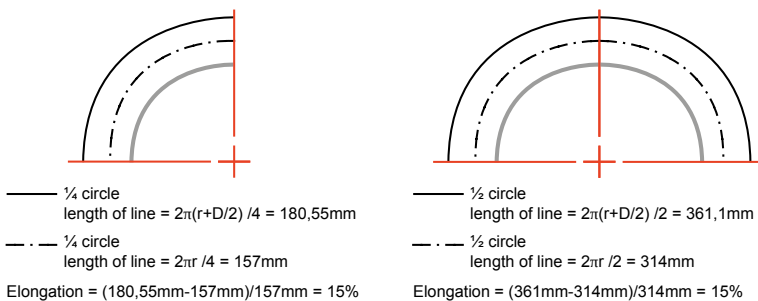
Figure 72. Effect of bending angle on elongation and minimum bending radius.

> **PRO TIP: Bending angle is not your problem, Bending radius is!**

4.5 Case study: bending troubleshooting

Figure 73. Hump at end of bend.

Hump at end of bend

1 Adjust the mandrel slightly back from the tangent until the hump is barely visible. This is also a good system to find the best location for the mandrel.

2 Program the software so that the mandrel is adjusted backwards 3-5° before bending is completed.

3 Increase force on pressure die assist.

Figure 74. Wrinkling throughout bend.

Wrinkling throughout bend

1 Test with wiper die.
2 Advance wiper die closer to tangent.
3 Decrease rake of wiper die.
4 Consider changing tube material to cold-rolled from hot-rolled.

Figure 75. Deep scratches throughout the bend and in wiper die area.

Deep scratches throughout the bend and in wiper die area

1 Increase rake.
2 Check for undersized mandrel.
3 Increase pressure die force only after checking wiper fit and mandrel location.
4 Reduce force on pressure die advance.
5 Use more and/or a better lube, e.g. consider IRMCO.

Figure 76. Tool marks on centreline of bend in clamp and pressure die area.

Tool marks on centreline of bend in clamp and pressure die area

1   Reduce pressure and clamp die forces.
2   Oversized tube or undersized tube groove from bad tooling source.
3   Adjust height of pressure die.

Figure 77. Excessive collapse with or without wrinkling throughout entire bend.

Excessive collapse with or without wrinkling throughout entire bend

1   Advance mandrel toward tangency until slight hump occurs (most mandrels must project somewhat past tangent)
2   Need more balls on mandrel
3   Select a tube with smaller dimensional tolerances

Figure 78. Mandrel ball humps.

Mandrel ball humps

1   Too much drag on tube; back off pressure die force – increase wiper die rake

2   May require closer pitch mandrel assembly.

3   Tubing material too soft.

4   Increase force on pressure die assist.

Figure 79. Wrinkles throughout bend area with wiper and mandrel in known position.

Wrinkles throughout bend area with wiper and mandrel in known position

1   Check for undersized mandrel.

2   Increase pressure die force only after checking wiper fit and mandrel location.

3   Reduce force on pressure die advance.

Figure 80. Bad mark at start of bend.

Bad mark at start of bend

1. Removable clamping portion of bend die not matched properly to round part of bend die.
2. Clamping portion of bend die not parallel to the key way.

Figure 81. Heavy wrinkles through bend area only and linear scratches in grip area indicating clamp slippage.

Heavy wrinkles through bend area only and linear scratches in grip area indicating clamp slippage

1. Reduce pressure die force.
2. Check location and lube of mandrel and wiper die.
3. Increase pressure on clamp die.
4. Use serrated or carbide spray in tube groove of clamp die

Figure 82. Tube bending defect: Mandrel seizing up with tube wall due to insufficient lubrication and wrong mandrel positioning and therefore breakage.

Figure 83. Tube bending defect: excessive tooling pressure and therefore scratching and breakage.

Figure 84. Tube bending defect: insufficient lubrication and therefore breakage.
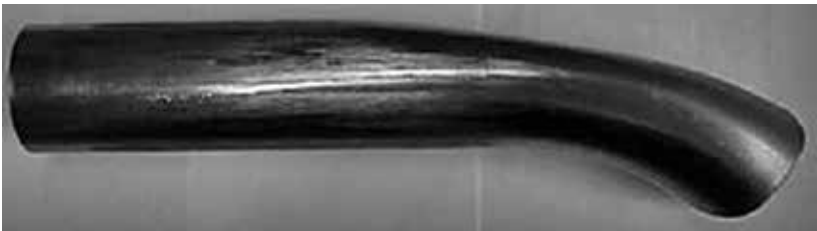
Figure 85. Tube bending defect: excessive flattening due to high D/T-ratio and bending without mandrel.

Figure 86. Tube bending defect: wrinkling due to extreme compression on inner radius.

Table 24. Practical minimum bending radii of thin-walled SSAB Form Tube 220 precision steel tube achievable by different bending methods with normal production tooling.

Bending method	Practical minimum bending radius	Failure with smaller than minimum bending radius
Push bending	8-15xD	Wrinkling
Roll bending	6-10xD	Wrinkling
Compression bending	4xD	Wrinkling
Draw bending, no mandrel	3.5-7xD	Wrinkling
Draw bending, with mandrel	2.0xD	Fracture
Booster bending	1.5-2xD	Wrinkling or fracture
Free radius bending	4-6xD	Wrinkling

PRO TIP: Don't try to bend a tube with CLR=3xD with roll bending.

4.7 Case Study: Cost savings with higher elongation

Higher elongation will provide a margin against failure in forming processes as well as higher deformation capacity such as tighter bending radii. In some cases, complex forming tooling may be replaced by a simpler and less expensive one. Ready tube components also have better tolerances and enhanced energy absorption. Enhanced elongation also makes allowance for changes in lubrication, tooling wear and adjustment precision.

It is well known that elongation value A is not very good parameter to be used in formability calculations in specific forming applications. Anyhow, A value has good correlation to general formability and well describes the change in formability when comparing different tube grades. SSAB Form Tube 220 has an elongation of 5 percentage units higher even compared with EN 10305 E220+CR2.

Table 25. Bending radii for tubes with 3 different guaranteed elongation at fracture values.

Steel Grade	Yield Strength [MPa]	Tensile Strength [MPa]	A [%]	Recommended minimum bending radius
E195+CR1 EN 10305	-	330	8	6.3xD
E220+CR2 EN 10305	220	310	23	2.2xD
SSAB Form Tube 220	220	310	28	1.8xD

A small bending radius is needed for
- Design reasons such as appearance, differentiation and artistic motive
- Engineering reasons such as simple construction and functionality
- Spacing reasons such as compatibility with other components
- Cost reasons such as reducing joining and increasing productivity

Figure 87 shows the distribution of elongation for E220+CR2 tube. The bell-shaped curve starts at 23% and the average elongation value is 38%. 5 percentage units of population is within the range of 23-28%. A 5% scrap rate is generally accepted in difficult high quality tube bending applications.

Figure 88 shows the distribution of elongation for SSAB Form Tube 220. Now the bell curve starts at 28%. If the bent tube component is designed based on 23% minimum elongation, there is a 5% margin for variables and it may be possible to manufacture bent components with a 0% scrap rate.
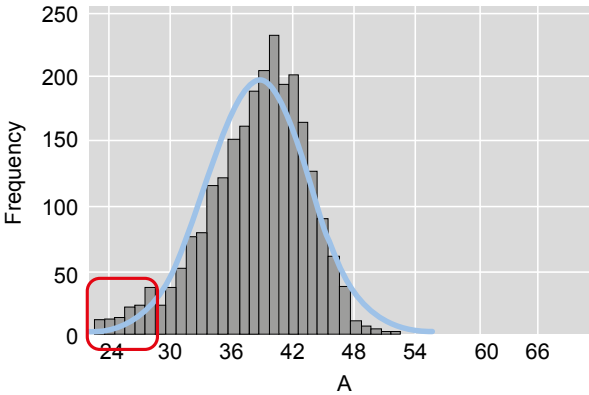
Figure 87. Bend component is designed for E220+CR2 tube with elongation of 23%. Due to bending process variation, there is a 5% scrap rate.
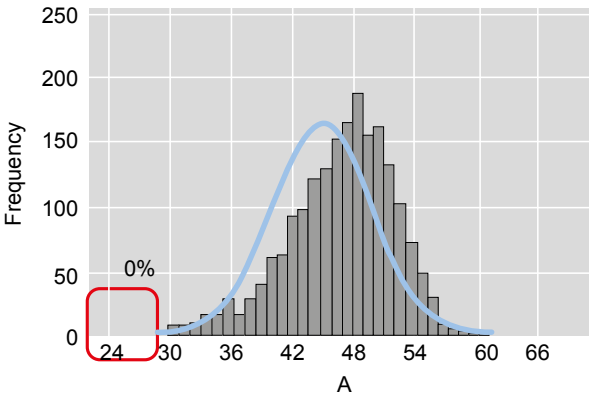
Figure 88. Bend component is designed for SSAB Form Tube 220 with elongation of 23%. Due to bending process variation, there is a 0% scrap rate.

PRO TIP: Material savings + reduced down time with SSAB Form Tubes, e.g. 5% with SSAB Form Tube 220.

4.8 Case study: Large and small bending radii and moment of resistance

When starting the manufacture of a new tubular component with a bending machine, it is sometimes necessary to evaluate whether the bending machine has enough force capacity. How will the steel grade, tube dimensions or bending radius affect the force needed?

Bending a tube into a new shape is a complex phenomenon to simulate mathematically without the aid of a computer. Tube bending includes elastic and plastic deformations and the deformations are large, which leads to several nonlinearities. Still we can use a simplified approach to evaluate how the bending radius affects the bending torque needed. We will keep the deformations small (small bending angle) and assume that the deformations are fully elastic.
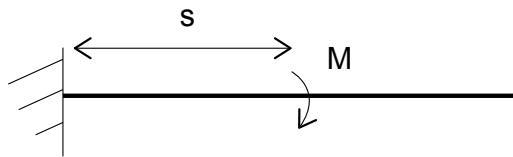
Figure 89. Tube bending.
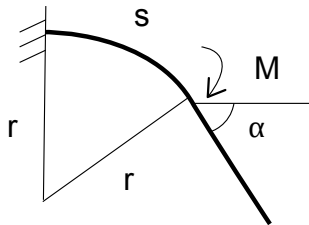
Figure 90. Tube bending, small bending radius.
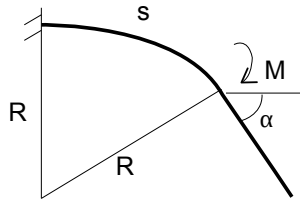
Figure 91. Tube bending, large bending radius.

$$\tan(\alpha) = \frac{M*s}{E*I} \tag{54}$$

Now we need to write the length s as a function of α and the bending radius. Let's use trigonometry to find the connection.
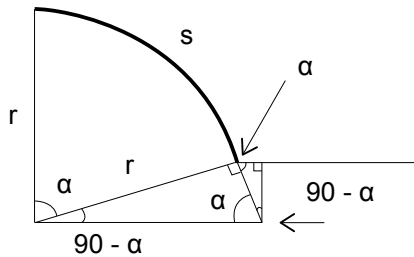
Figure 92. Arc length.

Now from figure 10 we get for small bending radius r:

$$s = \frac{\alpha}{2*\pi} * 2 * \pi * r = \alpha * r \tag{55}$$

For a large bending radius we need only to substitute r with R:

$$s = \alpha * R \tag{56}$$

Let's substitute s with α*r in the previous equation and solve the torque M:
Small bending radius (M = M_r):

$$M_r = \frac{EI}{r} * \frac{\tan(\alpha)}{\alpha} \tag{57}$$

Large bending radius (M = M_R):

$$M_R = \frac{EI}{R} * \frac{\tan(\alpha)}{\alpha} \tag{58}$$

For example let's assume that R = 2*r and divide M_R with M_r:

$$\frac{M_R}{M_r} = \frac{\frac{EI}{2*r}*\frac{\tan(\alpha)}{\alpha}}{\frac{EI}{r}*\frac{\tan(\alpha)}{\alpha}} = \frac{1}{2} \tag{59}$$

So we can see that if we double the bending radius the needed torque drops to half.

4.9 Case Study: Requirements for the "freischwinger" type chair

Freischwinger (cantilever) chair design has several important requirements for tube and design including:

- High load bearing capacity, e.g. 100 kg
- Small or large bending radius of tube depending on design
- Good surface quality for chromating
- Inside tube diameter tolerance for mandrel bending
- Elasticity of chair, it must be comfortable springy, not too stiff
- Low total weight for movable purposes
- High resistance against fatigue, particularly in pierced (hole) areas

In reality, chairs, like other furniture, are subject to many other requirements. They are tested according to related standards against several different factors, including stability and the fatigue of welded joints.

Figure 93. Typical design of freischwinger chair.

Example: Load bearing capacity of a freischwinger chair

Let's consider that the mass of a person sitting on the chair is distributed as a concentrated force on distance L from the corner of the chair (depending on in which point the person sits).
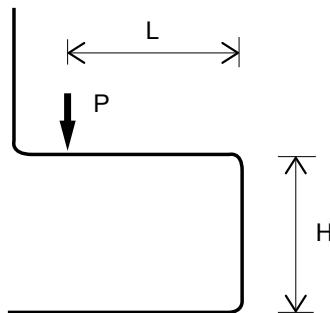
Figure 94. The freischwinger chair. L = 400 mm and H = 450 mm

The force W represents the gravitational force of the seated person. Because the chair is symmetric, we can conclude that the force P = m*g/2, where m is the mass of the person (100 kg) and g is the gravitational acceleration (9.81 m/s2). Since the structure of the chair is lightweight, we can neglect the mass of the chair in the calculations. Because the bending radius at the corners is small, we can generate following simplified representation for the calculations:
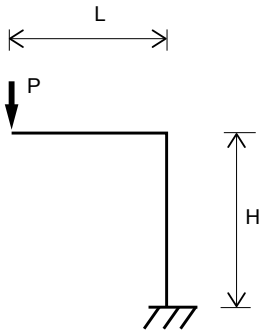
Figure 95. Simplified representation of the freischwinger chair.

Now we can draw a force equilibrium figure which is helpful in generating the equilibrium equations.
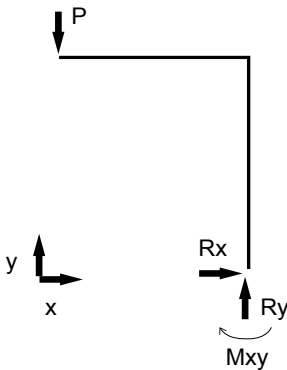
Figure 96. Force equilibrium.

The reaction forces and moment can be solved as follows (see Figures 92 and 93):

$$X-\text{direction:} \quad R_x - 0 = 0 \quad \longleftrightarrow \quad R_x = 0 \qquad (60)$$

$$Y-\text{direction:} \quad R_y - P = 0 \quad \longleftrightarrow \quad R_y = P \qquad (61)$$

The critical point for yielding is at the corner of chair, where the bending moment is at its highest and the compressive force parallel to the vertical member becomes zero. So the maximum stress σmax occurs at the same point. Let's calculate the maximum stress using the equation in Case study 3.8:

$$\sigma_{max} = \frac{M_{xy}}{W} = \frac{P*L}{W} = \frac{m*g*L}{2*W} \qquad (63)$$

Let's try 30x2 SSAB Form Tube 320 circular precision tube as the chair's structural element, which has the following cross-sectional properties:

Table 26. Cross sectional properties of 30x2 SSAB Form Tube 320

D/T	I [mm⁴]	W [mm³]	A [mm²]	E [N/mm²]
15	17329.03	1155.268	175.9292	210 000

For D/T ratio 15 the real yield stress σ_{yield} = 480 N/mm². Let's apply the values and we get:

$$\sigma_{max} = \frac{100\ kg*9.81\frac{m}{s^2}*400\ mm}{2*1155.268\ mm^3} \cong 170\ \frac{N}{mm^2} < \sigma_{yield} \qquad (64)$$

The real yield stress is 2.8 times higher than the maximum stress, so SSAB Form Tube 320 30x2 works fine.

Chair elasticity

Let's study the total deflection of the chair at the point where the force P reacts. Figure 97 illustrates the deflection of the chair:
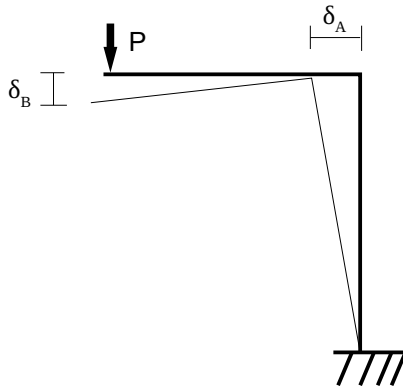
Figure 97. Chair deflection.

Now because the acting forces are known, we can solve the displacements δA and δB using the beam tables. Remember that P = m*g/2:

$$\delta_A = \frac{M_{xy}*H^2}{2*E*I} = \frac{P*L*H^2}{2*E*I} = \frac{m*g*L*H^2}{4*E*I} = \frac{100\ kg*9.81\frac{m}{s^2}*400\ mm*(450\ mm)^2}{4*210000\ N/mm^2*17329.03mm^4} =$$

$$5.46\ mm$$

(65)

$$\delta_B = \frac{P*L^3}{3*E*I} = \frac{m*g*L^3}{6*E*I} = \frac{100\ kg*9.81\frac{m}{s^2}*(400mm)^3}{6*210000\frac{N}{mm^2}*17329.03mm^4} = 2.87\ mm$$

(66)

Total deflection diagonally at the point where the force P reacts can be calculated using Pythagoras law:

$$\delta_{total} = \sqrt{\delta_A^2 + \delta_B^2} = \sqrt{(5.46\ mm)^2 + (2.87\ mm)^2} \cong 6.2\ mm$$

(67)

Freischwinger chair with a large bending radius

For comparison, let's look at the load-bearing capacity and deflection of a freischwinger chair with a large bending radius. Because the bending radius is large compared to the member's dimensions, we can make an accurate approximation that the elastic section modulus (W) and second moment of area (I) remains the same even though the member is curved.
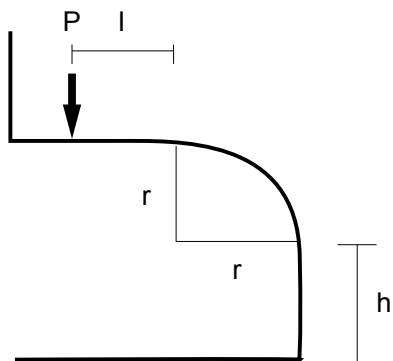
Figure 98. Chair with a large bending radius. l = L-r, h = H-r and r = 300 mm.

The critical point is at the end of the curve. Let's transfer the force P to the start of the curve and evaluate the forces at the end of the curve.
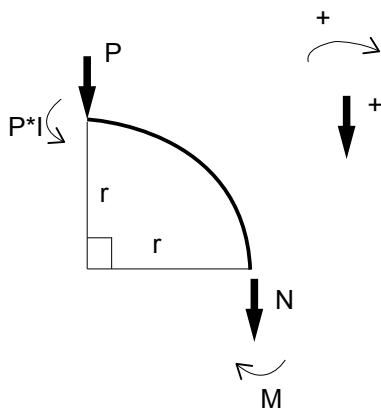
Figure 99. Chair's critical point.

$N + P = 0$ $\leftrightarrow$ $N = -P$ (68)

$M - P*l - P*r = 0$ $\leftrightarrow$ $M = P*l + P*r = P*(l+r) = P*L$ (69)

The maximum stress occurs at the outer edge of the member. The maximum stress is:

$$\sigma_{max} = \frac{N}{A} + \frac{M}{rA} + \frac{M}{I} * \frac{\frac{D}{2}}{1 + \frac{D}{2r}}$$ (70)

$$\sigma_{max} = \frac{-P}{A} + \frac{P*L}{rA} + \frac{P*L}{I} * \frac{\frac{D}{2}}{1 + \frac{D}{2r}} = \frac{-m*g}{2*A} + \frac{m*g*L}{2*rA} + \frac{m*g*L}{2*I} * \frac{\frac{D}{2}}{1 + \frac{D}{2r}}$$ (71)

Let's insert the values and we get:

$$\sigma_{max} \approx 163 \text{ N/mm}^2$$ (72)

The resulting stress is a bit lower than with the small bending radius.

Now we can calculate the deflection at the point where the force P reacts. The easiest method is to use the "beam tables".

Let's cut the structure into three parts:
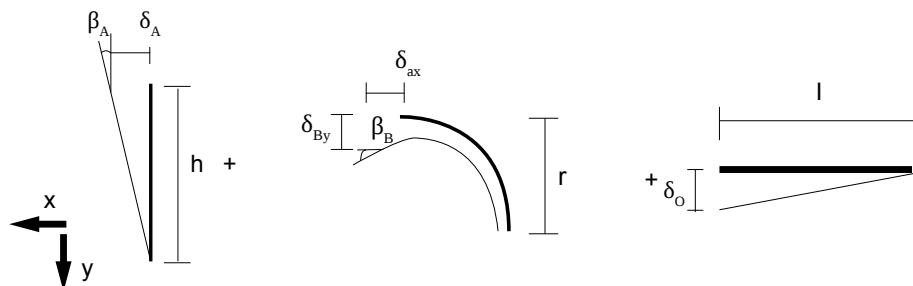
Figure 100. Deflection of the three parts.

Using Figure 100, we can now determine the deflections of these three parts:

$$\delta_A = \frac{M*h^2}{2EI} = \frac{PLh^2}{2EI} = \frac{mgLh^2}{4EI} = 0.61 \text{ mm} \tag{73}$$

$$\tan(\beta_A) = \frac{Mh}{EI} = \frac{mgLh}{2EI} = 0.0081 \tag{74}$$

$$\delta_{Bx} = \tan(\beta_A)r + \frac{Pr^3}{EI} * \frac{(1-cos90^o)^2}{2} + \frac{Plr^2}{EI} * \left(\frac{\pi}{2} - 1\right) = \frac{mgr}{EI} * \left(\frac{h}{2} + \frac{r^2}{4} + \frac{lr}{2}\left(\frac{\pi}{2} - 1\right)\right) = \tag{75}$$
2.52 mm

$$\delta_{By} = \frac{Pr^3}{EI} * \left(\frac{\pi}{4} - \frac{sin(2*90^o)}{4}\right) + \frac{Plr^2}{EI} * (1 - cos90^o) = \frac{mgr^2}{EI} * \left(\frac{\pi r}{8} + \frac{l}{2}\right) = \tag{76}$$
4.07 mm

$$\tan(\beta_B) = \frac{Pr^2}{EI} * (1 - cos90^o) + \frac{Plr}{EI} * \frac{\pi}{2} = \frac{mgr}{EI} * \left(\frac{r}{2} + \frac{l\pi}{4}\right) = 0.018 \tag{77}$$

$$\delta_C = \tan(\beta_B)l = \frac{mgrl}{EI} * \left(\frac{r}{2} + \frac{\pi l}{4}\right) = 1.85 \text{ mm} \tag{78}$$

Total deflection in x-direction:

$$\delta_{xtotal} = 0.61 \text{ mm} + 2.52 \text{ mm} = 3.12 \text{ mm} \tag{79}$$

Total deflection in y-direction:

$$\delta_{ytotal} = 4.07 \text{ mm} + 1.85 \text{ mm} = 5.92 \text{ mm} \tag{80}$$

Total deflection diagonally:

$$\delta_{total} = \sqrt{(3.12 \text{ mm})^2 + (5.92 \text{ mm})^2} = 6.7 \text{ mm} \tag{81}$$

We can see that the change in stresses and deflections is negligible if the chair's bending radius is increased when keeping the chair's dimensions unchanged. The large curvature distributes the stress more smoothly though.

If your structure includes curved members, using the theory of a curved member gives a more accurate result. But as you can see, the calculations then become much more complicated. On the other hand, the smaller the bending radius gets, the more and more accurate the simplified method becomes.

4.10 Case study: FE-simulation of draw bending with mandrel

FE-simulation has become more frequently used because of its possibilities to optimise the process and last but not at least able to reduce tooling cost. Regarding tube bending, the tool is more or less standardised, but for the entire process there are several options for the tooling setup and number of parameters that can be adjusted, e.g. with or without mandrel (insert), positioning of mandrel, booster, amount of feeding, etc. Below is a case from a typical FE-simulation of draw-bending, comparing the results between whether a mandrel is used or not.

Input data needed for simulation

Every type of FE-simulation requires inputs of material data explaining the properties, usually called a "material input card". The format for these cards differs depending on the FE-software used, but is usually written in a text-format as a Ascii format. The material data can then be visualised graphically with the FE software used or by the pre-processor. The pre-processor is software for preparing FE models with geometries, loads applied and material data. Figure 101 below shows a typical material model for FE simulation.
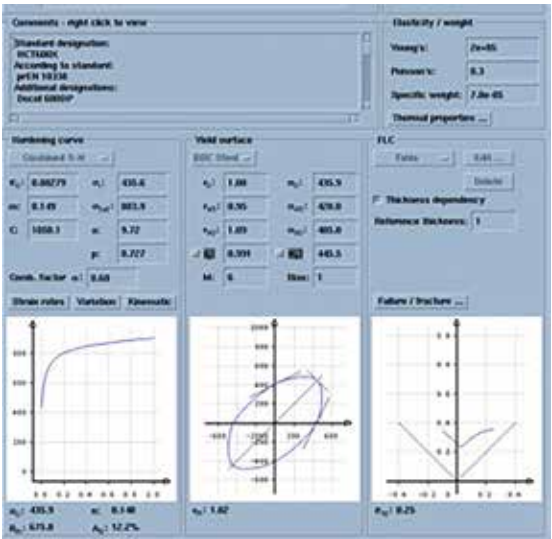
Figure 101. The material input representing Docol Tube 590, thickness 1 mm.

In Figure 101, the left curve shows the tensile test true stress - true strain data, extrapolated to 100% of strain. The reason behind extrapolating the tensile-curve is that the levels of strains become much larger in a tube bent compared within a tensile specimen in a tensile-test.

The diagram in middle shows the Yield surface, based on the yield stresses and r-values obtained from tensile tests performed in three directions, i.e. 0°, 45° and 90°. Finally to the right, an FLD diagram (Forming Limit Diagram) is shown. This type of diagram explains the maximum strain and strain path until material failure. Moreover, the FLD curve depends on the material-thickness. However, the main part of FE programs correct the FLD based on material thickness used compared to the reference curve. E.g. Autoform software for FE simulation has already prepared material data cards for several Docol Tube grades on the market, provided by different steel suppliers and easily selected by the user.

Input of tube geometry

Tube bending FE simulation is very simple (compared with process simulations for other types of sheet metal forming) as the geometry is more or less parameterised. The main geometrical measures are as follows: tube diameter D, material thickness T and bending radius CLR, see Figure 102. Additional parameter, l, set is the length of tube apart from the bend, see Figure 103.

Figure 102. The tube of geometry, D=45mm, t=1.5mm and CLR=90mm, i.e. 2xD.

Figure 103. Parameter described in Figure above, additionally parameter
l=141.37 mm, the length of the tube outside the bend.

Examples, tooling setup for draw-bending, with and without mandrel

The following two examples use different tooling setups. In the first example
(a), a mandrel is used and in (b) free bending is performed without a mandrel.
According to the slenderness, i.e. D/T=30, a wrinkling tendency is of course
expected. However, the result will be compared, trying to obtain a perfect
bend, using an insert. The issue is what type of mandrel to use, a spoon
mandrel only or ball mandrel. According to chapter 4.3 Mandrels, and the
Mandrel Chart Table, it is assumed that 2 balls are needed and that it is
preferable to add a wiper to the tooling setup to prevent wrinkling. In both
cases for simulation, the material thickness is T=1.5 mm, and the tube
diameter is D=45 mm.

The tooling, except for the mandrel, used in both examples, is shown in
Figure 104. The model of the mandrel is shown in Figure 105.

Figure 104. The die, wiper, pressure die and claws are shown.

Figure 105. The mandrel in accordance with the recommendation in the Mandrel chart, whereby a tube to be bent at a slenderness of D/T=30, requires a mandrel plus 2 balls to prevent wrinkling.

Results using mandrel or not

The results obtained of the final geometry of the bend are shown in the figures below. If using a mandrel, see Figures 106a and 107a, you can see that the inner surface of the bend is smooth and there are no tendencies towards buckling or wrinkling. If an insert is not applied, see Figures 106b and 107b, the cross-section of the bend is collapsed.

Regarding the risk of splitting, the so-called FLD (Forming Limit Diagram) is used, which shows the level of strains (cloud of dots) at different positions of the bend, see Figures 108a and 108b. These are compared with a material and thickness unique limit curve, representing the limit until failure (the solid curve). In this case, you can see that the calculated strains from bending simulation are all located below the limit curve, meaning low risk of splitting.

Apart from the result shown below, additional information can be read out from FE tube bending simulations, e.g. the amount of thinning of outer fibre and how much thicker the material will be at the inner radius of the bend.

Figure 106a. The result obtained using a mandrel.

Figure 106b. The bend will collapse without mandrel.
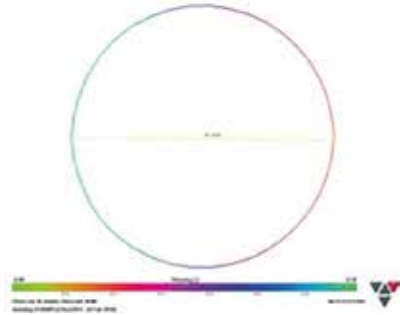
Figure 107a. Result of cross-section of stability indicating that the tube is still perfectly circular thanks to the mandrel used.

Figure 107b. The result of not using a mandrel, i.e. the cross-section has collapsed.
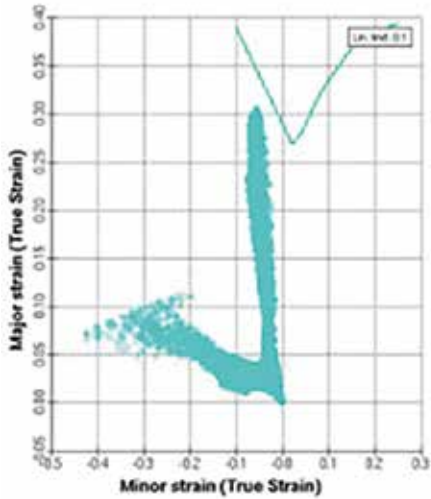
Figure 108a. Level of strains using mandrel.
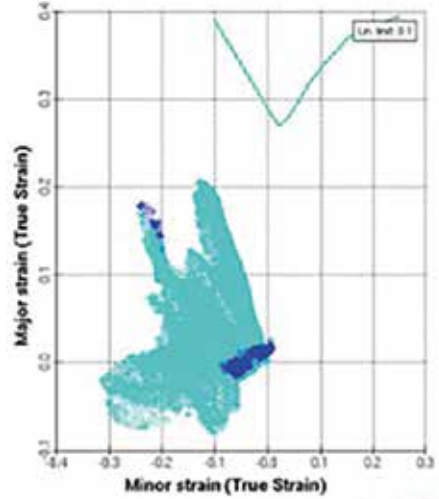
Figure 108b. Strains without using mandrel.

PRO TIP: Nothing special when bending galvanised (Z/GI) tubes: no need for special tooling and corrosion protection will remain. Carry on.

5. ARC welding

The design of welded joints aims at welds that are of optimal strength, look right and serve the intended application. Especially in robot welding, welding economy most obviously depends on factors such as the accessibility of the object, handling of the work piece, tool selection and quality assurance.

Proper consideration of dimensional accuracy at the work stages predicting the positioning, such as bending, flattening, milling or cutting to specified lengths, contributes to the weldability of a product. Shearing, punching, milling or thermal cutting can be used for preparation of the tube edges. The requirements on the edges are not very strict for ordinary arc welding.

The welding of precision tubes is usually done with fillet welds to join one precision tube to another or to thin sheet, such as a flange. Butt welds are mainly used for line pipe connections and tube accessories.

Because of the range of wall thicknesses of precision tubes, MAG (Metal Active Gas) short arc welding is the predominant method of welding. MIG (Metal Inert Gas) welding is not usually used in the welding of precision tubes, but the term MIG welding is often accidentally used in connection with MAG welding. High heat input is typical for arc welding in comparison with other welding methods, such as resistance spot welding or laser welding. The heat input can be calculated according to equation 82.

$$ \qquad (82)$$

Where
Q is Heat input [kJ/mm]
k is Arc afficiency, for gas metal arc welding k=0.8
U is Voltage [V]
I is Current [I]
v is Travel speed [mm/min]

TIG welding is used for high quality appearance. Gas, plasma and laser welding are complementary methods.

Figure 109. Welding. Courtesy of Kemppi Oy.

5.1 Weldability of SSAB Form Tubes

The risk of material-related weld defects is very low foror SSAB Form and Docol Tubes. The main reason for this is the chemical composition of steel grades. When evaluating tube weldability, it is justified to first consider the carbon equivalent value (CEV). The International Institute of Welding provides a simple and the most common way to calculate the carbon equivalent value of steels:

(83)

In practice, CEV means:
- For values above 0.40% there is a risk of hydrogen cracking in the weld's heat affected zone (HAZ)
- The lower the CEV, the better the weldability

Every steel grade used in the manufacture of SSAB's precision tubes has excellent weldability when using all conventional welding methods. The tubes owe their good weldability to low alloying and low carbon equivalent, even when compared with the requirements of EN 10305, see Table 27. The actual composition of SSAB Form Tubes shown in Table 27 includes 95% of the measured values. SSAB's precision tube steels are supplied as aluminium killed and with low nitrogen contents. Due to the low content of alloying elements and a very low amount of non-metallic inclusions, there is a low risk of welding defects, such as hot cracking or hydrogen cracking depending on the material.

Table 27. A comparison of the carbon equivalents (CEV) of SSAB Form Tubes and EN 10305 requirements. The carbon equivalent has been calculated using carbon and manganese elements only. See steel grade specific details for Si content: www.ssab.com.

In % by mass	C max.	Si max.	Mn max.	P max.	S max.	CEV max.
SSAB Form Tube 190	0.05	0.05	0.70	0.020	0.020	0.17
E190 EN 10305	0.10	0.35	0.70	0.025	0.025	0.22
SSAB Form Tube 220	0.10	0.05	0.70	0.020	0.020	0.22
E220 EN 10305	0.14	0.35	0.70	0.025	0.025	0.26
SSAB Form Tube 320	0.10	0.35	1.40	0.020	0.020	0.33
E320 EN 10305	0.20	0.35	1.40	0.025	0.025	0.43
SSAB Form Tube 420	0.12	0.50	1.70	0.020	0.020	0.40
E420 EN 10305	0.16	0.50	1.70	0.025	0.025	0.44

It should be noted that the standard gives only carbon and manganese contents used in formula (83). Other elements, e.g. those which are used for finishing a cast, are not included in the calculation.

In order to avoid corrosion damage, the tubes are normally coated with a thin oil film. However, this oil film is so thin that it does not give any porosity problems in conjunction with arc welding. However, if the tubes are stored in an environment where dirt may accumulate on their surface, some precautions have to be taken. In order to avoid welding defects in this case, some form of cleaning of the tube may then be necessary prior welding.

Welding of thin wall thicknesses places strict demands on the welding parameters used. To avoid burning through the wall and to minimise distortions, it is important to use a low heat input. Another benefit of low heat input is also a higher tensile strength of the welded joint. Preheating must not be used for SSAB precision steel tubes, not even at the highest strength levels. Filler metals for fusion welding have a strength level of 500MPa and above, so matching a base material strength to filler material strength is not an issue with steel grades up to SSAB Form Tube 420.

5.2 MIG/MAG welding

In MIG/MAG welding, an arc is created with the power supply through the welding gun between the welding wire being fed and the work piece. The arc fuses the material being welded and the welding wire, thus creating the weld. The wire feeder continuously feeds the welding wire through the welding gun throughout the welding process. The welding gun also provides shielding gas to the weld.

- MIG welding uses an inert shielding gas, which is not involved in the welding process
- MAG welding employs an active shielding gas that is involved in the welding process

Usually the shielding gas contains active carbon dioxide or oxygen, and therefore MAG welding is by far more common than MIG welding. A mixed shielding gas of argon and carbon dioxide is normally used in combination with either solid wire or cored wire. It is also possible to use pure CO_2 as shielding gas, but in this case the amount of spatter increases.

5.2.1. Equipment
MIG and MAG welding equipment typically comprises a power source, wire feed unit, grounding cable, welding gun, optional liquid cooling unit and a shielding gas bottle or connection to the gas supply.

The purpose of the wire feed unit is to feed the welding wire needed in welding from the wire reel to the welding gun. The wire feed unit also allows the power source to be started and stopped, and when using an electronic power source, controls the voltage provided by the power source. Therefore, the power source and the wire feed unit are connected by a control cable.

Additionally, the wire feed unit controls the flow of shielding gas. The shielding gas needed in welding is obtained either from a gas bottle or from a mains gas supply. The devices may also have a replaceable control panel and separately activated additional features.

Since the welding gun heats up during welding, it must be cooled with gas or liquid. In gas-cooled welding guns, the shielding gas running to the gun through the welding cable simultaneously acts as the gun cooler. In liquid-cooled guns, a separate liquid cooling unit is required to recycle the cooling liquid within the welding cable to the gun.

The structure of a MIG/MAG welding machine is restricted by the welding wire reel inside the machine. The reel is often a heavy and space-consuming component.

5.2.2 Welding technique

In MIG/MAG welding, the welder's tool is a welding gun. This is used to introduce the filler material wire, shielding gas and the required welding current to the work piece. The most important aspects related to MIG/MAG welding are the:

- welding position
- welding gun angle
- wire protrusion length
- welding speed
- shape of the molten weld pool

The arc is ignited using a trigger in the gun, which is then moved at a steady welding speed along the weld groove, and:

- the formation of the molten weld must be observed
- the position and distance of the welding gun relative to the work piece must be maintained constant

It is particularly important for the welder to concentrate on managing the molten weld at all times. A moment of wandering thoughts increases the risk of welding error. In such cases, it is advisable to discontinue welding for a moment and then resume.

5.2.3 Advanced processes

Synergic MIG/MAG welding

Synergic adjustment, or 1-knob adjustment, means that the wire feed speed is connected to the voltage and possibly other parameters. This makes it easier to find the welding values, as only one knob is needed for power adjustment.

The ease of adjustment is based on pre-set synergy curves, which are stored in the control panel of the welding machine. A guideline material thickness can also be connected to the synergy curves, which makes it even easier to adjust the welding parameters.

Pulse welding

In pulse welding, the power source pulses the welding current so as to move the filler to the groove one drop at a time. The peak current of the pulse is great enough to spurt the material into the groove, while the lower basic current keeps the molten weld and the end of the welding wire molten. The pulse feature requires the use of several inter-dependent welding parameters.

Pulse welding is primarily used in welding aluminium and stainless steels. Additionally, nickel and copper alloys are often welded with the pulse feature. The greatest benefit of pulse welding is the lack of spatters in the weld and its good appearance. With aluminium and stainless steels, pulse welding reduces porousness. With nickel alloys and other difficult-to-weld materials, the pulse method makes welding easier. This makes pulse welding an attractive method for welding galvanised materials.

Double-pulse welding

In double-pulse welding, you can pulse also the wire feed speed in addition to the regular pulsing features. This means that the wire feed speed varies during welding and the user can adjust amplitude and frequency variation. This enables adjustment of the desired penetration and creates clean welds. It also helps to control the weld pool in various welding positions.

The frequency of a double pulse refers to the number of times a double pulse is repeated in one second, and the amplitude refers to the magnitude of the change. This affects weld appearance and heat input.

5.2.4 Special features

Welding devices equipped with remote control speed up welding, particularly in an installation environment. Using a remote control improves work quality and productivity as the welder does not have to move to the machine every time when changing welding parameters.

Welding arc properties can be affected for example by the following special features.

Optimal arc length

Keeping optimal arc length and consistent weld quality in all welding positions may be difficult. One solution to this problem is WiseFusion, which is an optional function for Kemppi FastMig Pulse and KempArc Pulse welding machines.

WiseFusion creates and maintains an optimal short circuit characteristic in pulsed MIG/MAG and spray-arc welding applications. For both manual and automated welding, WiseFusion eliminates the need for regular parameters adjustments:

- automatic arc length regulation
- excellent weld pool control for positional welding
- narrow and energy dense arc
- improved weld quality and appearance

High-quality root welding

For effective closure of root joint areas and also the accommodation of gaps created by poor joint fit-up, one possibility is WiseRoot+, which is a highly efficient and unique tailored cold arc process for manual and automated root pass welding.

WiseRoot+ is three times faster in root closure than TIG welding, is easy to learn and use, and saves time on rework costs. Traditionally, welding engineers have been reluctant to employ the standard MIG/MAG process for quality root welding, due to known quality issues.

The process involves a very precise real-time measurement of voltage (voltage sensing cable), which serves as the input for the current control. Once the power source has recognised a short circuit, a controlled increase in current triggers the transfer of a droplet of filler metal from the wire.

When the current measurement is exactly right, the current is dropped before the filler-metal droplet falls and the short circuit ends. A short circuit ending at a point of low current results in a smooth transfer of filler metal, with no spatter. After the short circuit is broken, a pulse is created in the current that heats the welding pool, but does not cause transfer of filler metal.

Advantages of root welding solution:

- three times faster than TIG welding
- easy to learn and use
- saves rework costs
- allows wide root gap tolerance
- no need for backing ring or ceramics
- produces high quality root welds
- can decrease joint volume in thick materials reducing required filler materials volume

Thin tube walls and brazing

Design features and lightweight applications such as automotive manufacturing and high-quality light fabrication may require a cold-arc process for manual and automated thin-wall welding or brazing. An example of a specially-tailored process for these purposes is WiseThin, which:

- reduces spatter with all materials including zinc-coated plates
- provides 10–25% lower heat input than normal MIG/MAG welding, reducing post-weld material distortion
- excellent weld pool control with varying joint geometry and fit-up
- reduced post-weld rework
- increased welding speed in many applications

Some welding applications - such as joining quenched boron steels, dual phase steels or heavy metallic coated steels - may require lesser heat input than traditional MAG welding. Due to the lesser heat input in arc brazing, the base materials do not melt and so the metal coating is not damaged or thin structures distorted excessively. When arc brazing galvanised precision steel tubes, zinc will also vaporise because of the melting point of brazing wire, which is higher than the vaporisation point of zinc. Since zinc evaporation is considerably less than in MAG, the joint will also have better corrosion properties.

Arc brazing is a variation of the MAG process: the arc heats the material being welded and melts the brazing wire, the molten wire moistens gap surfaces and the molten wire solidifies to create a weld. Arc brazing wire is copper based, e.g. CuSi3, CuSn6 or CuAl8. A drawback of this method is wire costs, which may be five times higher than normal MAG wire.

Figure 110. Arc brazing, butt joint.

Figure 111. Arc brazing, flange joint.
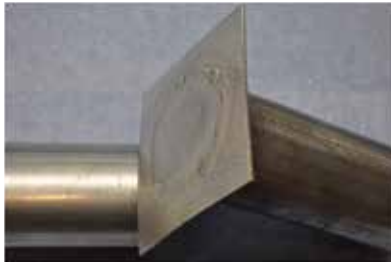
Figure 112. Due to low heat input in arc brazing, zinc remains on the galvanised surface.

5.3 TIG method

In TIG welding (Tungsten inert gas), the welding arc is formed between a non-consumable tungsten electrode and the work piece. The shielding gas is an inert gas that does not affect the welding process per se. Usually, the shielding gas is argon and it protects not only the molten weld, but also the electrode in the torch from oxygenation.

A filler material may not be necessary in TIG welding. The pieces can be fused also by melting the groove together. If a filler is used, it is fed into the molten weld manually and not through the weld torch as in MIG/MAG welding. Therefore, a TIG welding torch has a completely different structure than a MIG/MAG torch.

5.3.1 Equipment

TIG equipment consists of a:
- power source
- grounding cable
- welding torch
- shielding gas bottle or gas network connection
- machine that may also contain a liquid cooling unit

No wire feed unit is required as the filler material is manually fed, although auto-feeding systems also are available.

5.3.2 Welding technique

In TIG welding, the torch is moved with one arm while the other feeds the filler material to the molten weld. A TIG welder must, therefore, accurately control both arms and one cannot be used to support the torch as in MIG/MAG welding.

These special requirements make TIG welding more difficult, particularly in the beginning. However, the arms will soon adjust to the paths of motion required in welding and TIG welding becomes routine. Nevertheless, complex TIG welding is usually done by a welder specialising in TIG welding.

TIG welding is done with a pushing torch motion. The filler can be fed into the weld either drop by drop or continuously, keeping the filler wire constantly in the molten weld.

5.3.3 Advanced processes

AC/DC

TIG welding methods are classified according to the welding current into DC TIG and AC TIG for direct current and alternating current, respectively. TIG welding power sources are suitable for both current types (AC/DC) or for only DC welding.

DC welding is typically used in welding a variety of metals. Alternating current must, however, be used in aluminium welding to break the aluminium oxide on the part surface.

If a mixed current of both direct and alternating current is used in TIG welding, the method is called MIX TIG welding. This is a particularly useful method when welding aluminium materials of different thicknesses together.

If a mixed current of both direct and alternating current is used in TIG welding, the method is called MIX TIG welding. This is a particularly useful method when welding aluminium materials of different thicknesses together.

Pulsed TIG

In Pulse TIG welding, the power source pulses the welding current, which reduces the heat effect affecting the material being welded. This is useful particularly when welding thin materials in which the TIG heat input is great. Pulse welding also improves the manageability of the molten weld pool and the penetration.

5.3.4 Efficient TIG welding

The selection of the shielding gas can affect the fusing and penetration of the basic material. The most commonly used shielding gas in TIG welding is argon. Its benefits are its low price and good shielding effect, combined with the ignitability of the arc. Its weakness is its poor thermal conductivity and the subsequent potential problems in the smooth fusing of the weld. Fusing can be improved by adding 5-25% hydrogen to the shielding gas. This will also reduce the area of the arc and increase penetration. Hydrogen can be used with austenitic stainless steel.

Using helium as the shielding gas allows for good merging of the filler with the basic material and produces good penetration. However, its weakness is in the poor ignitability of the arc. This can be improved by using a mixture of helium and argon.

5.4 Welding gun selection

The welding gun is selected according to the requirements of the application, but also depends on welder's preferences. It is important to ensure the required standard of quality and convenience.

5.4.1 MIG/MAG welding guns

The welding gun is selected according to:
- welding current
- welding performance
- joint type
- groove geometry
- welding position.

PMT Multineck

The PMT air cooled multi-neck gun system is designed especially for welding root passes on pipes and plates.

Changeable neck liners

Water- and liquid-cooled MIG/MAG welding guns with different power handling are available. Also so-called changeable neck liners are available. Select the best neck length, bending angle and gas nozzle for the welding task head, allowing good reach and control. Install the neck assembly firmly to gun handle.
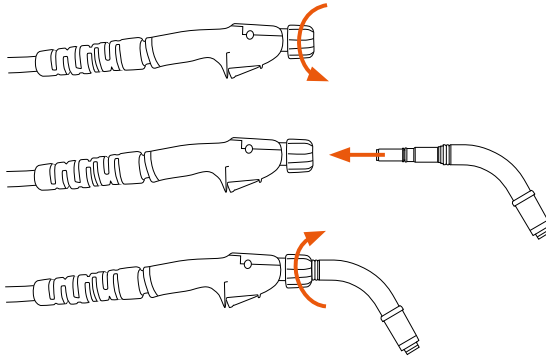
Figure 113. Hand tightening of changeable neck liner.

5.4.2 TIG welding torches

Welding current, shielding gas and HF-ignition combine in the torch to make welding possible. Welding torches are available in different sizes and designs, both gas- and liquid-cooled. The torches are equipped with a function switch to control the current, for example.

Torch shape:

- torches with a 120° neck angle are the most used model in manual welding and are highly suitable for fillet welds and butt joint welding in all positions
- torches with a 90° neck angle are suitable for pipes and butt joint welding.
- when the torch handle is parallel to the pipe, the pipe surface provides light support for the welder's hand during welding. An angle torch is not suitable for fillet welds or performance becomes difficult.

The wearing parts of a torch are:
- Gas nozzles/gas lenses
- Electrode shields
- Neck 120°

Figure 114. TIG torch wearing parts.

Figure 115 and Tables 28 and 29 provide a short overview of TIG torch angle and electrode information.
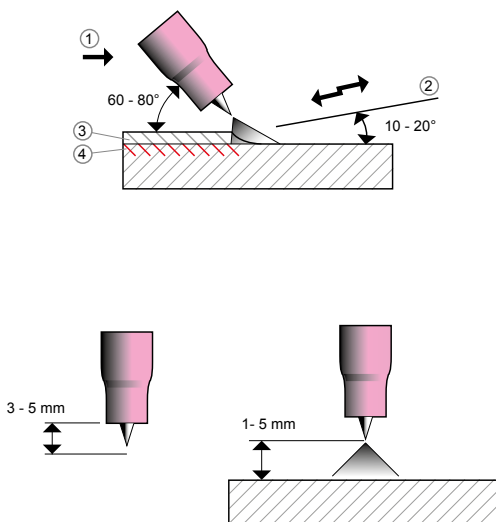
1. welding direction
2. filler wire
3. weld
4. penetration

note: welding without filler wire TIG torch angle is 75–80°.

Arc length depends on used current and joint type.

Figure 115. TIG torch angle.

Table 28. TIG electro info.

Code	Alloy	Colour code	Use
WP	100% W	Green	(AC)
WC 20	98% W + 2% Ce	Gray	AC / DC
WT 10	99% W + 1% Th	Yellow	DC (AC)
WT 20	98% W + 2% Th	Red	DC
WT 30	97% W + 3% Th	Lilac	DC
WT 40	96% W + 4% Th	Orange	DC
WZ 8	99% W + 1% Zx	White	(AC)
WL10	99% W + 1 La	Black	AC / DC
WL 15	98.5% W + 1.5% La	Gold	AC / DC

Table 29. TIG gas nozzles.

Electrode diameter	Gas nozzle n:o	Gas flow l/min.	Current Rane A
Ø 1.6	4-5	5-7	20-130
Ø 2.4	5-6	6-8	100-250
Ø 3.2	6-7	7-9	150-350
Ø 4.0	7-8	8-10	200-500

Gas nozzle n:o is a multiply of 1/16", e.g.: n:o 5 is 5x1.5875 mm = 7.9 mm

5.5 General welding defects in MIG/MAG welding

Unstable arc and spattering
- wire feeding disturbances
- poor earth connection to the work piece
- worn-out contact tip
- (problem in power source)

Porosity
- spatters in the gas nozzle and contact tip
- gas flow rate too low or high
- damaged gas nozzle
- gas leakages in the gun or its connections
- faulty gas flow regulator
- water leakages in a water-cooled gun

Disruptions in the wire feeding
- feed rolls are slipping.
- blocked or worn-out wire conduit.
- wire conduit too long or too short.
- wire reel brake too tight or loose

Figure 116. Lack of fusion.

Lack of fusion

Possible causes	Avoidance
• too narrow joint preparation • incorrect electrode angle • too high current or too low welding speed will cause weld pool flooding ahead of the arc resulting in insufficient penetration	• use a sufficiently wide joint preparation • ensure the electrode angle gives adequate side wall fusion • select welding parameters (high welding current, short arc length and not too high welding speed) to promote sufficient penetration without causing flooding • clean joint faces • move the position of the earth clamp, use as short an arc as possible, reduce the welding current, angle the electrode opposite to the direction of arc blow, use AC power source

Figure 117. Porosity.

Porosity

Possible causes	Avoidance
• poor gas shielding • wet electrode • impurities of the joint faces e.g. rust • too thick primer layer faulty polarity	• seal any air leaks, reduce excessively high gas flow rates, avoid weld pool turbulence, avoid draughts • dry the electrode • clean the joint faces • check to ensure the primer thickness is below manufacturer's maximum • change the polarity
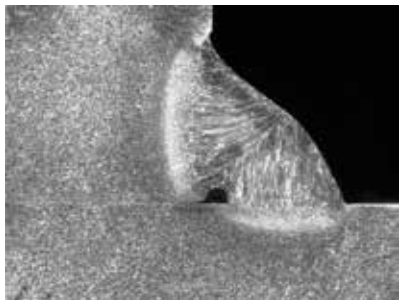
Figure 118. Slag inclusions.

Slag inclusions

Possible causes	Avoidance
• voids caused by inadequate overlap of two adjacent weld beads • insufficient slag removal • too low heat input • slag flooding ahead of the arc • too narrow joint	• use the correct size and angle of electrode, use welding techniques to produce smooth weld beads • remove all slag between runs • increase the heat input • aim the arc toward weld pool • increase the joint angle

Figure 119. Undercut.

Undercut

Possible causes	Avoidance
• a wide spreading arc with low current or high welding speed • incorrect angle of the electrode • excessive weaving of the electrode • too high current	• weld with a shorter arc / reduce the voltage • use proper electrode angles • perform the weaving motion properly by pausing at each side of the weld bead • reduce the current

Figure 120. Excessive asymmetry of fillet weld

Excessive asymmetry of fillet weld

Possible causes	Avoidance
• incorrect electrode angle • too large weld pool • magnetic arc blow	• use proper electrode angles • reduce the deposition rate • move the position of the earth clamp, use as short an arc as possible, reduce the welding current, angle the electrode opposite to the direction of arc blow, use AC power source

Figure 121. Excess weld metal.

Excess weld metal

Possible causes	Avoidance
• too much filler metal in relation to welding speed • electrode diameter too large	• increase the welding speed or • reduce the amount of filler metal • use proper electrode diameter or increase the joint angle
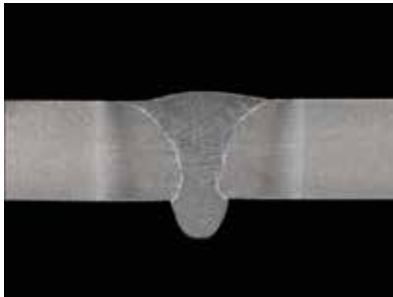
Figure 122. Excessive penetration.

Excessive penetration

Possible causes	Avoidance
• too high heat input to the joint • too large joint gap • too small root face	• reduce the heat input • use appropriate joint fit-up • enlarge the root face

Figure 123. Cracks, e.g. hot crack.

Cracks, e.g. hot crack

Possible causes	Avoidance
• too low width to depth–ratio of the weld • high stresses due to high thermal expansion • incorrect filler metal/base metal combination • base metal surface covered by oil, grease, moisture, rust etc. • too high welding speed	• ensure that the width to depth ratio of • the weld is over 1 (with non-alloy steels) and over 1,5 (with stainless steels) • minimise the degree of restraint by using correct edge preparation and accurate joint fit-up • use crack-resistant filler • properly clean base metal prior to welding • reduce the welding speed

Figure 124. Lack of penetration.

Lack of penetration

Possible causes	Avoidance
• poor joint design or preparation • excessively long arc length • electrode diameter too large • welding speed too fast	• increase root opening or decrease root face • weld with a shorter arc / reduce the voltage • use electrode with a smaller size • decrease the welding speed

Figure 125. Linear misalignments.

Linear misalignments

Possible causes	Avoidance
• poor component fit-up before welding • deformations during welding • breaking of tacks during welding	• perform joint fit-up work accurately • fix parts to be welded rigidly, use correct welding sequence • perform tack welding properly
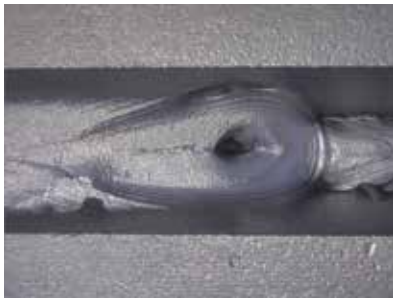
Figure 126. Crater crack and crater pipe

Crater crack and crater pipe

Possible causes	Avoidance
• this imperfection results from shrinkage on weld pool solidification • switching off the welding current will result in rapid solidification of a large weld pool • faulty stopping technique	• stop welding by transporting the arc a little backwards or in the groove side • progressively reduce the welding current to reduce the weld pool size • grind the stop before continuing the welding

Figure 127. Spatter.

Spatter

Possible causes	Avoidance
• faulty welding parameters • too long arc / high voltage • wet, uncleaned or damaged electrodes • impurities of the fusion faces and the filler materials, e.g. rust • magnetic arc blow • faulty polarity	• adjust the welding parameters • weld with a shorter arc / reduce the voltage • use dry and undamaged electrodes • grind the fusion faces and use • the clean filler materials • change the position of the earth clamp / weld towards earth clamp / bend the stick/torch in the direction of the blow • change polarity

5.6 Case study: Modern MIG/MAG equipment

Welding machines are evolving rapidly: besides the advanced processes described earlier, advances also in user interfaces, design, energy saving and productivity are growing in leaps. An example of these developments is the Kempact RA:
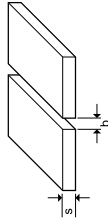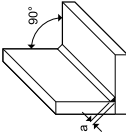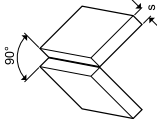
Table 30. Modern MIG/MAG equipment.

- Plexiglas cover and lens plate
- Regular (R models) or Adaptive (A models) control panel interface.
- 2-roll or 4-roll wire drive systems.
- Inverted gun connection
- Brights™ wire cabinet lighting
- WireLine™ service symbol
- Integrated storage trays for wire drive and gun parts.
- GasMate™ chassis
- Strong pressed steel and moulded plastic construction
- Welding polarity terminals
- Particle filter option

Kempact Adaptive (A) models
- power setting by plate
- thickness control
- filler materials selection
- memory channels

HotSpot™ feature allows metal shrinking and component heating.

5.7 Case study: MAG welding parameters

Table 31 below presents some welding parameters for the MAG welding of non-alloyed structural steels. These parameters can be used e.g. with SSAB Form 220 tube.

Table 31. Welding parameters for MAG welding.

Plate thickness s mm	Gap b mm	Wire diam. ø mm	Deposition rate kg/h	Wire feed speed m/min	Welding current A	Voltage V	Travel speed cm/min
1	0	0.6	1.0	7.0	60	16.0	83
1.5	0.5	0.8	1.2	6.0	90	17.5	80
2	1	0.8	1.5	6.8	110	18.2	83
3	2	0.8	1.8	8.0	125	19.2	55
3	2	1.0	2.1	6.0	150	18.5	63

Plate thickness s mm	Throat thickness A	Wire diam. ø mm	Deposition rate kg/h	Wire feed speed m/min	Welding current A	Voltage V	Travel speed cm/min
2		0.6	1.2	8.4	70	16.5	40
2		0.8	1.6	6.8	110	18.2	53
3		0.8	1.9	8.3	130	19.5	32
3		1.0	2.4	7.0	170	19.0	40

Plate thickness s mm	Gap b mm	Wire diam. ø mm	Deposition rate kg/h	Wire feed speed m/min	Welding current A	Voltage V	Travel speed cm/min
1.5		0.6	1.0	7.0	60	16.0	83
2		0.8	1.6	6.8	110	18.2	88
3		0.8	1.9	8.2	130	19.5	63

5.8 Case study: welding galvanised surface

Metal-coated tubes, Z/GI, ZA and ZF/GA are well suited for welding. Gas metal arc welding is a good choice to weld zinc coated tubes. However, due to the special nature of metal coatings, some aspects need to be addressed. First of all, the thinner the metal coating, the easier the tubes are to weld. Typically, a zinc coating up to 100…140g/m^2 is well suited for short-circuit transfer mode. If the total coating mass is higher, the risk of welding errors and spatter also increases.

Spatter and errors can be reduced considerably by selecting a suitable welding method, welding wire and shielding gas and by lowering the wire feed, welding current and/or travel speed. If the quality of the weld needs to correspond to a weld in an uncoated tube, it might be advisable to remove the zinc layer in the weld area. Using a shielding gas with a high proportion of CO_2 increases the heat supply, which decreases the porosity.

The reason for welding problems with galvanised surface is that zinc quickly gasifies during welding. The gasification temperature of zinc is 907°C, which is much lower than the melting temperature of steel, which is about 1500°C. This affects the arc and it may sometimes be difficult to weld in the normal way.

ZF/GA-coated tubes are especially well suited for spot welding and can be welded with a low current. Additionally, welding electrodes require maintenance at longer intervals.

If the aim is to maintain as much zinc as possible around the weld area, the heat input can be limited by selecting another type of weld joint or method. Applicable methods include pulsed welding, arc brazing, laser welding and CMT (cold metal transfer).

When metal coatings containing zinc are welded, zinc oxide particles (zinc oxide fumes) are released into the air. Extensive exposure to these fumes causes zinc fever. It is therefore often recommendable to use a fume extraction welding gun, improve the local exhaust system or use an air-fed welding mask. The concentration of zinc fumes can be determined by taking work hygiene measurements.

Fresh air helmets:
- welding and grinding rated to EN175B
- fresh air helmet is a head unit providing protection against arc welding, gouging, grinding operations and associated air-borne fume and dust contamination

- provide safe, clean and cool breathing air
- air flow reduces weld lens misting
- standard lens or auto darkening welding filter option
- the shield design also incorporates a perimeter deflection rim, offering additional protection in overhead welding applications and the dual-skin hatch design reduces heat transfer to the welders face
- fresh air helmets can be combined with either a battery powered filter pack or locally supplied breathing air sources

Figure 128. Fresh air helmet is use. Courtesy of Kemppi Oy.

Welded joints in metal-coated tubes can be protected against corrosion by painting or thermal spraying. Before applying the protective coating, any welding residue should be removed by abrasive blasting, brushing or some other method.
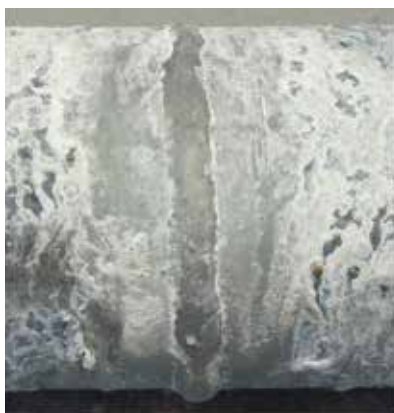
Figure 129. MAG-welded joint of zinc-coated tube after salt spray test without (left) and with zinc spray protection (right).

Figure 130. ARC-brazed joint of zinc-coated tube before (left) and after (right) salt spray test with zinc spray protection.

> **PRO TIP: If zinc removal on steel surface is needed, a hydrochloric acid (HCl) water solution will work: soak and flush.**

5.9 Case study: MAG welds of high strength tubes

High heat input is typical for MAG welding and then soft zones in HAZ of the high strength steels will follow. A soft zone can be seen as a decrease in hardness and strength. A soft zone may be compensated by increasing the length of the weld, but excessive softening may be avoided by adjusting welding parameters to lower heat input, in which case preheating is unnecessary, too.

The hardness and strength of MAG welds increases with increasing steel strength and can be altered by using a low or high strength fillers, see Figures 131...134.

Figure 131. Hardness profile of Docol Tube 590. Low strength filler R_m=560MPa.

Figure 132. Hardness profile of Docol Tube 590. High strength filler R_m=890MPa.

Figure 133. Hardness profile of Docol Tube 780. Low strength filler R_m=560MPa.
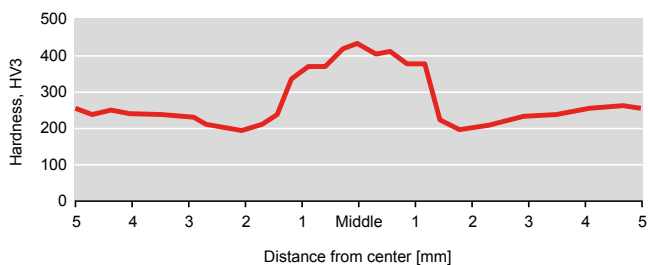
Figure 134. Hardness profile of Docol Tube 780. High strength filler R_m=890MPa.

6. Coatings and treatments

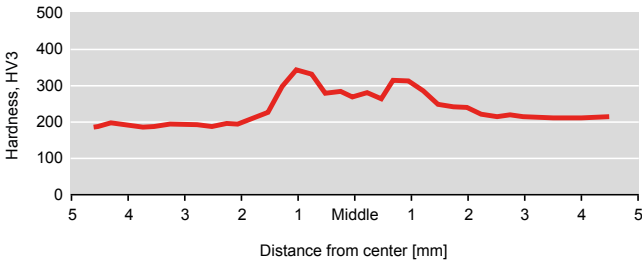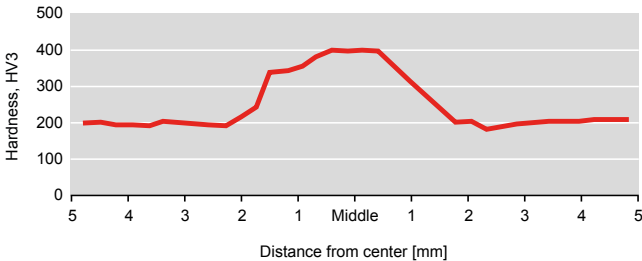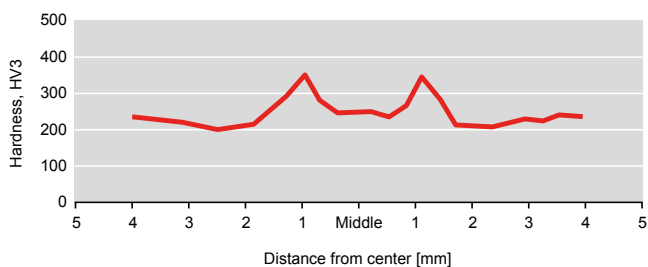Coating precision tubes is one way to improve corrosion resistance and to improve surface appearance. Precision tubes can be coated with metals or by painting. Different metal coatings can be applied in various ways. This chapter gives an overview of different coating properties and coating methods.

There are many different coatings including pure zinc coatings, alloyed zinc coatings (aluminium, magnesium), chrome plating and painting. Different zinc-rich coatings are continuous hot-dip galvanised zinc coatings, such as Zinc, Galfan, Galvanneal, Aluzinc and Zinc-Aluminium-Magnesium, batch hot-dip galvanised and electroplated. Chrome plating could improve corrosion resistance and result in a gloss surface. Paint coatings consist of primers, undercoats and top coats and are applied by powder coating or wet painting.

6.1 Continuous hot-dip galvanising

Zinc coatings provide excellent galvanic protection against corrosion. The zinc in the coating protects the underlying steel even if the coating is cracked. Table 31 shows a comparison between different zinc and zinc-alloyed coatings, their properties and appearance. SSAB currently produces continuous hot-dip galvanised tubes (Z/GI), Galvannealed tubes (ZF/GA) and Galfan tubes (ZA). Coating thickness is also a factor in various tube properties such as weldability and corrosion resistance. As a general rule, the thicker the coating, the better the corrosion resistance. Correspondingly, tube weldability deteriorates as coating thickness increases. See Chapter 5 for more information about welding.

Table 31. Properties of different metal coatings.

Zinc (Form Tube Z, Docol Tube GI)	Galvannealed (Form Tube ZF, Docol Tube GA)	Galfan (Form ZA, Docol ZA)
• Zinc coating ~100% Zn • Semi-gloss finish • White corrosion product	• Zinc-iron coating ~90% Zn, ~10% Fe • Matt finish • Reddish corrosion product	• Zinc-aluminium coating 95% Zn, 5% Al • Gloss finish • White corrosion product
• High galvanic protection • Good corrosion resistance in different atmospheric conditions • Good formability • EN 10346	• Less galvanically active (10%) • Extremely low cut-edge corrosion • Optimal surface for painting • Excellent corrosion resistance when painted • Good weldability • EN 10346	• Extremely high galvanic protection, especially in extreme atmospheric conditions • Good formability • EN 10346

Other metal coatings mentioned earlier such as batch hot-dip galvanised, Aluzinc, Zinc-Aluminium-Magnesium exist on the market, but SSAB does not currently produce them. Table 32 gives a brief overview of these coatings.

Table 32. Properties of different metal coatings not currently produced by SSAB.

Batch hot-dip galvanised	Aluzinc	Zinc-Aluminium-Magnesium
• Zinc coating ~100-72% Zn, ~0-28% Fe • Semi-matt finish • White and reddish corrosion product • High galvanic protection • Good corrosion resistance in different atmospheric conditions • EN ISO 1461	• Zinc-iron coating ~55% Al ,~45% Zn • Semi-gloss finish • White corrosion product • Good corrosion resistance • EN 10346	• Zinc-aluminium-magnesium coating (amounts depends on different producers, different amount have a different properties) • Good corrosion resistance in high salinity atmosphere • Is not yet standard coating

Zinc coatings can be made using different manufacturing methods, which produce different surfaces depending on appearance and corrosion properties. For example, batch hot-dip galvanising provides the thickest zinc coating and largest zinc spangles compared to continuous hot-dip galvanising or electroplating.

SSAB's Form Tubes Z, ZA and ZF are manufactured from continuous hot-dip galvanised coils. The zinc coating and passivation are applied on the galvanising line.

Zinc

Continuous hot-dip galvanised zinc coating has good, homogenous surface quality compared to batch hot-dip galvanised coating. Changing the continuous hot-dip galvanising parameters enables different zinc coating thicknesses. Today, SSAB can produce zinc coating thicknesses in the range of 100-600g/m² (minimum total coating mass, both surfaces) which means 7-42µm (theoretical guidance values for coating thickness per surface in the single spot test).

Galfan

Galfan is applied on the same continuous galvanising line as zinc coating and differs from zinc coating in bath concentration. Galfan is an aluminium-alloyed zinc coating containing around 95% zinc and 5% aluminium. Alloying the aluminium to zinc gives better corrosion resistance, especially in offshore conditions. Galfan is a thinner coating than continuous hot-dip galvanised zinc.

Today, SSAB can produce Galfan coating thickness in the range of 95-300g/m² (minimum total coating mass, both surfaces) which means 7-23µm (theoretical guidance values for coating thickness per surface in the single spot test).

Galvannealed

Galvannealed coating is produced in almost the same way as zinc coating, the difference being the galvanneal furnace after the zinc bath. In the galvanneal furnace, the zinc coating is annealed to the zinc-iron alloy containing around 10% iron. Because Galvannealed coating is intended for painting, only thin coatings are produced. Its thin coating and Fe content make Galvannealed particularly suitable for spot-welding. Today, SSAB can produce Galvannealed coating thickness in the range of 100-140g/m² (minimum total coating mass, both surfaces) which means 7-8µm (theoretical guidance values for coating thickness per surface in the single spot test).

Aluzinc and zinc-aluminium-magnesium are also produced on the continuous galvanising line.

Figure 135. Precision tubes are both for acrobatics and traffic signs. Pole dance Finnish champion Henriikka Roo. Photo: Keskipohjanmaa/Clas-Olav Slotte.

6.2 Batch hot-dip galvanising

In the batch hot-dip galvanising process, the steel to be coated is cleaned, pickled and immersed in a zinc bath. Before the coating is applied, the steel surface is cleaned by abrasive blasting or grinding to remove all marking,

coating or welding slag. The cleaning step also includes the removal of oil and grease, usually with an alkaline degreasing solvent, and the removal of rust and mill scale by pickling in hydrochloric acid or sulphuric acid.

The zinc coat thickness is determined by the intended application, which also determines the appearance of the product. The thickness and appearance of zinc coatings depend on the following circumstances:

- The silicon and phosphorus content of the steel
- The zinc bath temperature, immersion and cooling times, and alloying elements
- Surface finish of the steel

According to standard EN ISO 14713-2, the steels can be divided into four different categories based on their silicon content. These categories and properties are shown in Table 33 below.

Table 33. The impacts of silicon content on batch hot-dip galvanising and the requirements regarding silicon and phosphor content. Based on standard EN ISO 14713-2.

	Typical levels of reactive elements	Typical coating properties
	Category A (cold rolled steel): Si≤0.03 and P< 0.02 and Si+2.5P<0.06 weight-%	Bright, shiny and fine texture. The outer layer is zinc.
	Category B: 0.14 - 0.25 weight-% Si	Zinc coating is thicker than category A. Surface colour difference may appear because the Fe/Zn alloy may extend through the coating surface and surface can be mattish.
	Category C: 0.04<Si≤0.14 weight- %	Too high coating thickness is possible. Surface is dark and coarser texture.
	Category D: Si> 0.25 weight-%	Coating thickness increases with increased silicon content. The surface is darker and has coarser texture. Fe/Zn alloys dominate the coating structure and extend to coating surface.

Precision tubes are not usually batch hot-dip galvanised. The maximum values regarding silicon and phosphor content under precision tubes standard EN 10305 are not compliant with batch hot-dip galvanising properties.

SSAB Form Tubes H and 190-320 C comply with typical alloying requirements of Category A and are suitable for batch hot-dip galvanising. Where a better surface quality and good corrosion resistance are required, SSAB Form Tubes Z600 are a better choice. SSAB Form Tubes Z600 have as good a corrosion resistance as batch hot-dip galvanised (75µm) tubes, see chapter 6.7.

Hot-dip galvanising is normally carried out within the temperature range of 450-460ºC. The usual zinc bath temperature is 440-470ºC. At this temperature range, the thickness and appearance of the zinc coating essentially depend on the composition of the steel and the immersion time.

Figure 136 shows the dependence of zinc layer thickness on the silicon content of the steel at a temperature of 460ºC, with two alternative immersion times.

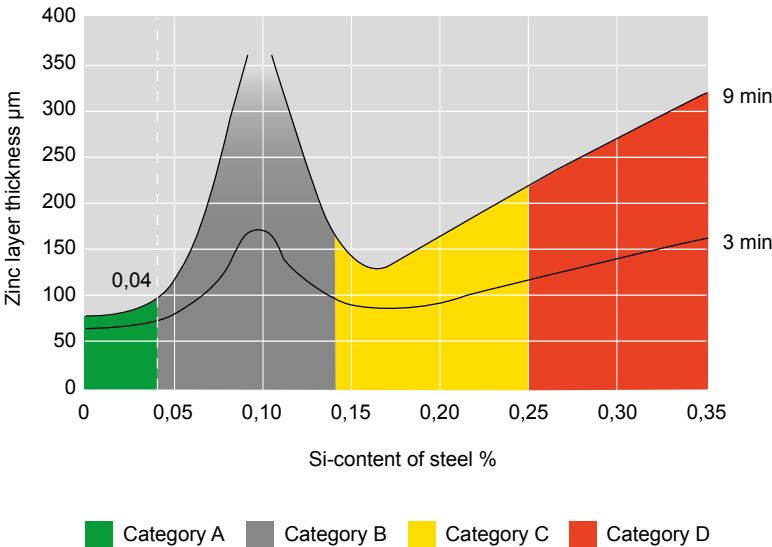**Figure 136.** The dependence of zinc layer thickness on the silicon content of steel. Temperature 460ºC. Immersion times 3 and 9 min.

Different steel grades with the same silicon content behave in approximately the same way and also obtain almost the same coating thickness. Zinc layer thicknesses over 100µm are not achieved in high-temperature zinc baths. The zinc coatings turn out matt, dark or light grey in colour.

Increasing surface roughness increased the zinc coating thickness. Depending on the steel grade and steel profile, shot blasting, for example, could result in a 15-100% thicker coating. Heavily rusted and heavily pickled steel receives thicker zinc coatings. Different machining affects coating thickness. Gas and laser cutting, for example, normally have an effect on thinner zinc coatings.

In standard EN ISO 1461 for hot dip galvanizing, the local minimum zinc layer thickness with material thicknesses 1.5≤t≤3 mm is determined as follows:

- Local coating thickness (minimum) 45μm
- Mean coating thickness (minimum) 55μm

The local minimum zinc layer thickness with material thickness t<1.5mm is determined as follows:
- Local coating thickness (minimum) 35μm
- Mean coating thickness (minimum) 45μm

Other aspects taken into consideration in batch galvanising are the effect steel thickness has on zinc coating thickness. The thinner the steel, the thinner the zinc coating. One of the reasons for this is the shorter handling time in the zinc bath. A small amount of aluminium alloying (0.001-0.01%) is used in the zinc bath for a brightened surface. If the aluminium alloying is too high, black spots form on the surface where there is no zinc coating. In addition to proper choice of material, the structural details of a product must be designed for hot-dip galvanising. Parts which are hot-dip galvanised are dipped into acid and then molten zinc. When a part is dipped into molten zinc, the residual pickling solution vaporises and causes a risk of explosion. This is why tubular structures and containers need drains. Design values for drains are given in Table 34 below.

Table 34. The design values for drains in hot-dip galvanising.

Tube dimension [mm]	Drain dimension [mm]
under 15	10
15-30	10-15
30-50	2x15
50-100	2x20
100-200	2x50

More batch hot-dip galvanising designs can be found in standards EN ISO 14713-2 and EN ISO 1461.

6.3 Electro galvanising

Electro galvanising or zinc electroplating is based on an electrochemical pair where the zinc layer is deposited onto the tube surface by electroplating. Before the zinc electroplating process, the tube is degreased and cleaned by pickling. The specimens are dipped into a zinc salt solution (cyanide zinc baths, alkaline non-cyanide bath or acid bath), which is the electrolyte. The cathode (the object to be plated) is dipped into a solution to which a direct-current is supplied. The anode (the metal used for plating) is bare zinc in the shape of a plate or ball. When the current is switched on, the zinc dissolves from the anode to the cathode. Temperature is one parameter in the electroplating process and is required to be 12...55°C. Electroplated coating is used especially when it is not possible to use hot-dip galvanising because it requires a high temperature. Electroplated zinc is very fine-crystalline and it adheres to the steel only mechanically. For a more vivid appearance, the surface may be furnished with an ornamental pattern made by grinding before coating. Zinc layer thickness usually ranges from 5μm to 8μm, but thicknesses of 3μm to 25μm are possible under standard SFS-EN ISO 2081.

The design of products to be zinc electroplated should contain the structural details required for successful zinc coating. Sharp corners and narrow slots that trap the coating solution should be avoided and adequate drains must be provided.

Chromating the zinc coating improves the corrosion resistance of the product (against white rust) and it is also possible to change the colour of the coating in conjunction with chromating treatment. Depending on the treatment, coatings of different colours and different corrosion resistance are obtained. Possible colours include black and olive green. The colour range is further extended by the possibility of colour bleached chromate coatings. In the case of products to be painted, paint adhesion can be improved by phosphating.

The surface quality of precision tubes affects the electroplating surface quality. A pickled-electroplated surface has a mattish surface compared to the surface of a cold-rolled electroplated surface. SSAB recommends using steel grades from SSAB Tube 190 C to Docol Tube 980 C tubes for electroplating.

6.4 Chrome plating

Chrome plating is produced in an electro-galvanic coating process, appropriate drains and the degrading of tube ends, where needed, must be taken into consideration in the production steps preceding coating. In the coating process,

the work piece is first cleaned of rust protection oil and other impurities. First, a bright nickel layer is deposited on the tube surface and then a thin chromium layer. The thickness of the bright nickel layer is normally 10-35µm and the thickness of the chromium layer 0.3-2µm.

Copper plus nickel plus chrome coatings are also used and their corrosion resistance is better than that of bright nickel plus chromium coatings. Copper-based coatings are mainly used in products for outdoor applications where it would be too expensive to provide a corresponding degree of corrosion resistance just by making the nickel-chromium coating thicker.

The bright chromium layer reinforces the gloss of nickel, prevents oxidation and discolouring of the nickel layer and gives high resistance to wear. Chrome coatings can be divided into the following types:
- conventional chrome plating (macrocracks)
- black chrome plating (non-cracked)
- micro-cracked chrome plating
- micro-porous chrome plating

Although black chrome plating has performed excellently in corrosion tests, it does not actually give higher corrosion resistance. Mechanical shock, such as a stone hitting the coated surface, easily causes the chrome coating to crack whereupon the chrome no longer protects the nickel coating against corrosion. Micro-cracked and micro-porous chrome platings have mainly been developed for ornamental automotive components that are required to have high corrosion resistance.

The quality control of metallic coatings mainly focuses on appearance, coating thickness and adhesion. Corrosion resistance can be determined by accelerated corrosion tests and the adhesion of the coating to the substrate by filing tests or a thermal shock test specified to standard EN ISO 2819. Defects affecting the appearance include bubbles, pores, coarse spots, cracks, stains or miscolouring. The surface finish may be specified in the order as bright, matt or satin.

When planning a coating of nickel plus chromium, it is important to know the aggression of the surroundings it will be exposed to. Standards divide coatings into five classes according to service conditions. Standard EN ISO 1456 for electroplated coatings of nickel plus chromium rates a minimum thickness of 10µm of the nickel layer on the better side as service condition 1. In service condition 2, the minimum thickness is 15µm. The corresponding minimum thickness for copper plus nickel plus chromium is 10µm of copper and 5µm of

the nickel layer on the better side as service condition 1. In service condition 2, the minimum thickness is 15μm of the copper layer and 10μm of the nickel layer.

Chrome plating on precision tubes are mainly provided in service condition 1, partly also in service condition 2. The appearance of the chrome-plated surface quality of precision tubes involves direct savings in coating costs.

Surface defects resulting from the material and preceding work stages are clearly visible on chrome plated objects. Defects in form (blister left by a mandrel, shear caused by clamp jaws, uneven elongation on the outer bow, flattening, orange peel, etc.) easily show up on a chrome plated tube.

On square or rectangular tubes, the weld is more visible than on circular tubes. This is mainly because light is reflected differently on a flat and curved surface. Square and rectangular tubes can be ordered with the weld so positioned that it will not show on the outward turned surfaces of finished product.

In electro-galvanising, the operator seeks to control the spread of the metallic coating on complex objects so as to give every recess and protrusion of the surface an even coating. With the tube correctly positioned, the pinching effect of the electric field on the outer bend can be utilised. This gives a thicker coating on the outer bend than on the rest of the tube.

Coating costs are higher for complex objects containing, e.g. sharp corners, narrow slots where the coating liquid may collect or recesses that increase the consumption of coating material and time.

The cost of coating correlates to the surface roughness of precision tubes in the same way. A good finish is achieved using tubes with a surface roughness, Ra, typically below 0.6μm in the longitudinal direction of the tube. The surface roughness of SSAB Form Tube 220 C to 420 C is under 0.6μm

If the steel grade has a tendency to develop orange peel in connection with stretch forming, it may be necessary to grind the surface for exacting applications. In tests with tubes of cold-rolled steel as a test material, excellent surface quality has been achieved with normal chrome plating consisting of 15-20μm nickel and ca. 0.3μ chromium.

According to the above-mentioned tests, grinding is not needed in the case of bent precision tubes made of SSAB's steels Form 190 C, Form 220 C, Form 320 C, Form 420 C and Docol 590 C because the surface quality of a bent tube is equal to that of an unbent tube.

Figure 137. High gloss chrome plated Sola chairs including SSAB Form Tube 18x2. Courtesy of Martela Oyj.

6.5 Washing

The metal surfaces can have different impurities such as light oil, protective grease, salt, carbon dust, dust, machining liquids, metallic chips, rust or rust film. Most of those are easily removed by washing with water. Grease which has had a long time to dry is problematic. Washing parameters (washing agent, time, temperature, movement) should be correct for the impurities to be removed. To ensure the right washing, the material to be washed (steel, zinc-coated steel, aluminium, etc.), the quantity of impurities, the type of impurities, the type of washing used and how clean a surface is needed must be known. Solvent degreasing, alkali wash, acid cleaning or emulsion cleaning are usually used to remove grease and oil. The washing agents consist of an active ingredient (for example, sodium hydroxide in alkali washing), inert ingredients and tensids.

Alkali washing is the most common form of washing steel surfaces. Heavily alkali washes etch zinc and it is recommended to keep the pH between 5 and 11, 12 at the maximum. Higher pH will damage zinc coatings. If an alkali wash is used for zinc or aluminium, special ingredients are used to reduce zinc and aluminium etching. Alkali washing is done by dipping or spraying. Zinc-coated surfaces can be washed with acid cleaners, which do not etch the zinc coating. Common alkali, emulsion or solvent degreasing does not remove white rust nor the chromates produced through passivation of the sheet steel material.

6.6 Painting

Plain, uncoated precision tubes made of cold-rolled steel, hot-rolled and pickled steel are equally suitable for painting. Metal coatings provide an excellent surface for painting. Of the above, Galvannealed is the best alternative for painting, as its surface is even and slightly structured. Painting is easy and paint adheres well to the surface. Thanks to its galvanic properties, zinc protects the steel even if a small area of the paint film is damaged.

The stock precision tubes made by SSAB are usually lightly oiled. Tubes delivered coated with protective oil and subsequently washed during the painting process are extremely well suited for powder coating or wet painting. However, if paint is applied on a passivated coating, the paint will blister in humid conditions. Chemical pre-treatments suitable for zinc coatings include zinc phosphating or the various recently developed chrome-free multi-metal treatments. Orange peel possibly resulting from the forming of the tube has no major effect on the painted finish. Standard EN-ISO 12944 parts 1-8 are used for testing and planning the coated parts.

6.6.1 Surface pre-treatment

The pre-treatment steps before painting are degreasing, acid pickling, conversion coating and rinsing. Chapter 6.5 contains more information about washing. Acid pickling, where needed, is used to remove oxides. Phosphating/conversion coatings are used for improved paint adhesion and to remove impurities after washing. Rinsing is the last process before painting. Rinsing must be done thoroughly to ensure a good final result in painting.

Zinc and iron phosphating are used as phosphate coatings. Iron phospating is the most common, but is not recommended for zinc-coated steels, because it is only an acid wash to zinc. Zinc phospating is an excellent pre-treatment for zinc-coated steel where excellent corrosion resistance and paint adhesion are required.

6.6.2 Powder coating

In powder coating, a pre-treatment object is coated with powder. The pre-treatment steps before powder coating are degreasing, acid pickling, conversion coating and rinsing. Powder coatings are almost 100% solid matter. Powder coating is usually done using air injection. Powder coating can be done on an automatic or manual line. Once powder coated, the object is hardened in an oven. Oven time depends on the powder coating, object shapes and thickness.

With proper surface treatment also a hot-dip galvanised surface can be powder coated. Baking oven treatment for a galvanised surface, curing oven temperature and curing time allow Docol Tubes to bake harden. Bake hardening increases the strength of the steel.

Figure 138. Outdoor sport & fitness, painted tubes. Courtesy of HAGS Aneby AB.

6.6.3 Wet painting

Solvent- and water-borne paints are usually spread as a spray or dip-painting. Spray coating is used in the automotive industry. In spray coating, the wet paint is fed into a nozzle which smoothly forms a coating on the substrate. In dip painting, the object to be painted is dipped into a paint basin. Dip painting is especially good for painting complex objects.

6.7 Corrosion resistance of SSAB's coatings

Zinc coatings provide excellent galvanic protection against corrosion. The zinc in the coating protects the underlying steel even if the coating is cracked. As a general rule, the thicker the coating, the better the corrosion resistance. Table 35 shows the estimated durability of different zinc coatings in atmospheres corresponding to the corrosivity categories of standard EN ISO 9223. The estimates are based on environmental tests carried out in various outdoor testing grounds.

Table 35. The corrosion resistance of different coating types according to different corrosivity categories. The corrosivity categories are those specified in standard EN ISO 9223. The durability estimates are based on outdoor testing in various outdoor testing grounds.

Coating type	Coating mass, total for both surfaces [g/m^2]	Coating minimum durability in atmosphereas corresponding to corrosivity category C2	Coating minimum useful life in atmospheres corresponding to corrosivity category C3
Z/GI	100	10	6
	275	27	17
	450	45	28
	600	60	38
ZA/ZA	255	70	50
ZF/GA	100	15	7

Figure 139 provides an example of how increasing the thickness of a coating influences its corrosion resistance in different atmospheric conditions. As shown in Figure 139, Form Z600 has an estimated durability of more than 80 years in atmospheric conditions typical for Finland and Sweden. Correspondingly, Form Z600 has an estimated durability of 60 years in a low-salinity coastal atmosphere, which is one of the most demanding atmospheres in the C2 corrosivity category. Thanks to its good corrosion resistance, Form Z600 tube can be used in place of hot-dip-galvanised tube in some applications, reducing overall costs. The Finnish Transport Agency has already approved the use of the galvanised Z600 tube in traffic sign posts.
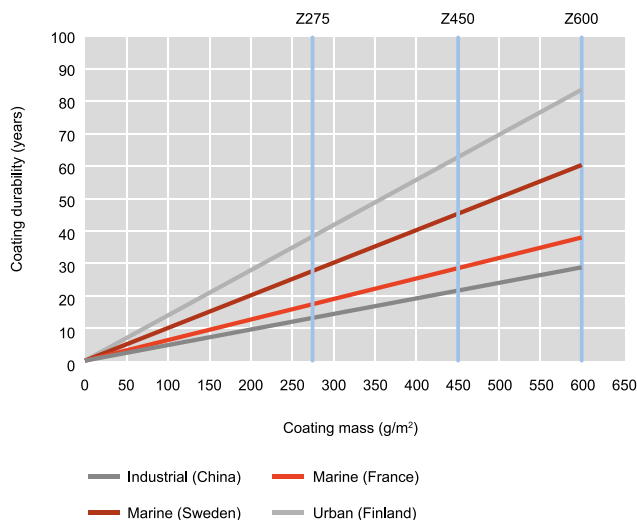
Figure 139. The estimated durability of a zinc coating in atmospheres corresponding to different corrosivity categories, other durability factors excluded.

Compared to SSAB Form Z Tubes, tubes coated with ZA (Galfan) have better corrosion resistance in coastal and marine environments. Figure 140 shows the corrosion resistance of zinc and Galfan coatings in atmospheres corresponding to different corrosivity categories.
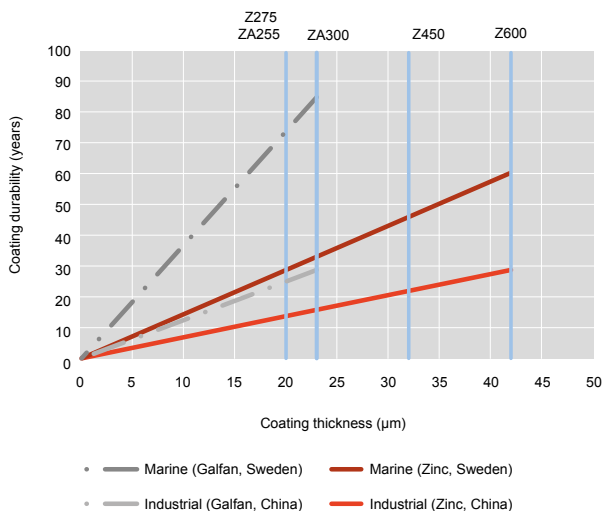

Figure 140. The estimated durability of zinc and Galfan coatings in atmospheres corresponding to different corrosivity categories, other durability factors excluded.

A comparison of SSAB Form Z tubes to batch hot-dip galvanised tubes shows that a 75μm batch hot-dip galvanised coating typically has the same corrosion resistance as SSAB Form Tube Z600 in marine and urban environments. Figure 141 shows the corrosion resistance of zinc and batch hot-dip galvanised coatings in atmospheres corresponding to different corrosivity categories.
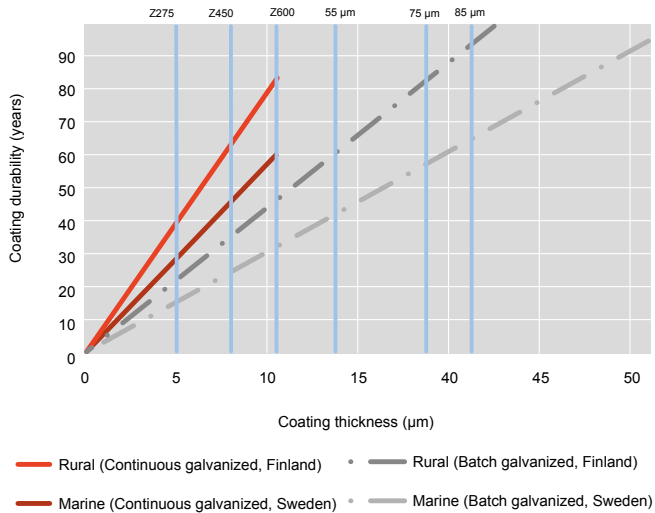
Figure 141. The estimated durability of zinc coatings in atmospheres corresponding to different corrosivity categories, other durability factors excluded.

In Figures 139-141, Sweden marine corresponds to corrosion class C2 minimum and France marine corresponds to the corrosion class C3 minimum. Those corrosion classes are based on standard EN ISO 9223.

PRO TIP:
Z100 for light corrosion protection
Z275 for moderate corrosion protection
Z600 for heavy corrosion protection

6.8 Case Study: Lifetime of ZA255 in corrosion class C3

Coating lifetime depends on environmental corrosivity factors such as temperature, relative humidity, SO2 deposition and Cl deposition. Standard EN ISO 9223 determines zinc corrosion rates in different categories, see Table 36. There is quite a wide difference between the lower and top end corrosion rates in category C3: from 0.7µm/a to 2.1µm/a. This is due to variation between zinc coatings and environmental circumstances. It is also worthwhile considering how transport and storage of products in different categories, especially in higher corrosivity category, impacts on total lifetime.

Table 36. Corrosion rate of zinc in different corrosivity categories for the first year of exposure according to EN ISO 9223.

Corrosivity category	Typical atmospheric environment	Corrosion rate of zinc	
		g/m²a	µm/a
C2	Rural areas, small towns, warehouses	0.7-5.0	0.1-0.7
C3	Urban, industrial and coastal areas with low chlorides, food processing plants, laundries	5-15	0.7-2.1
C4	Industrial and polluted urban areas, coastal areas without spray of salt water	15-30	2.1-4.2
C5	Very high pollution, significant effect of chlorides	30-60	4.2-8.4

Usually, accelerated corrosion tests such as QCT or SST do not give the right result for evaluation of long term behaviour. On the other hand, it is known that after the beginning of exposure, 1 year or so, the corrosion rate decreases. However, here it is assumed that the corrosion rate is linear with time because zinc and zinc alloys vary significantly in their performance as suggested in standard EN ISO 9224:2012.

According to the standard approach, ZA255 coating would withstand corrosion of between 17 and 51 years in category C3. According to real outdoor exposure test results, see Figure x, the lifetime would be from 25 (high end of C3 category) to 75 years (low end of C3 category). It can be concluded that the lifetime of ZA255 in corrosion class C3 is approximately 50 years.

6.9 Case Study: corrosion-resistant frames

When producing frames especially prone to varying weather conditions, there are some aspects to consider such as appearance, lifetime costs and environmental impact. A key element in this kind of structure is material selection and possibilities to optimise final outcome originating from material. Below is a description of how Z600 coating would behave in frames from various points of view.

Presumption

Frame made of SSAB Form Tube 320, dimensions 60.3x2 and total frame weight 10 tonnes. Figure 142 shows the basic elements to be taken into account when handling the overall situation. Because of the assumption of long-term corrosion resistance and desired strength level of tube, batch hot-dip galvanising is a practical alternative for Z600 coating.
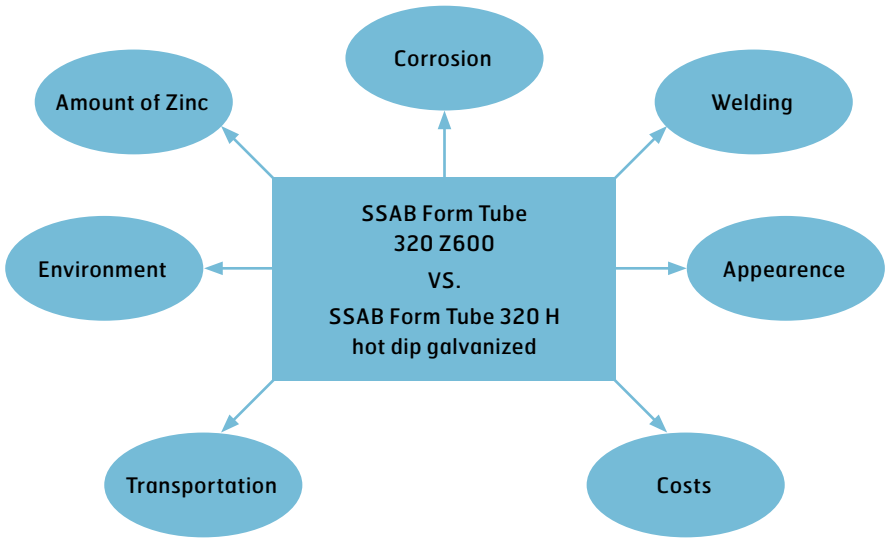

Figure 142. Some factors to consider when designing frames.

Corrosion

The desired lifetime for zinc coating will determine the choice of coating thickness. In batch hot-dip galvanising, coating thickness could be e.g. 75-85µm. This is a suitable choice if very long, more than 80 years in corrosion class C2, corrosion resistance is required.

SSAB Form Tube with Z600 coating has a lower corrosion rate than batch hot-dip galvanised coating and thus corresponds to coating thickness 75µm, see Figure 141. One factor providing this lower corrosion rate is passivation, which is normally applied to the surface. With batch hot-dip galvanising, the cutting edge is covered with zinc. The cutting edge of Z600 is protected by the galvanic distance effect, where the exposed steel is cathodically protected. This distance effect depends on atmosphere and in a normal atmospheric environment is appr. 1mm. Shear cutting of zinc coated steel can shift some zinc to shear portion of cut face, giving some extra protection on it, see Figure 143.

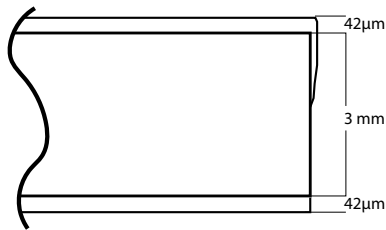**Figure 143.** Schematic cross section picture from cutting edge.

The corrosion product of Z600 coating is white rust and with batch hot-dip galvanising is a mixture of white and red rust originating from the Zn/Fe phase. See Figures 144 and 145 for examples of different corrosion resistance and corrosion products.

Figure 144. 24h in QCT 60°C. Left picture is Z600 and right one is hot dip galvanized.
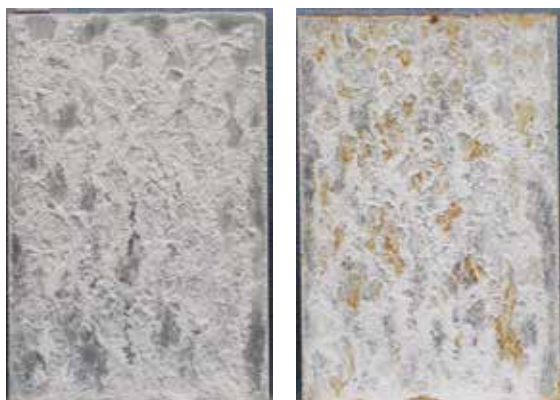
Figure 145. 500h in SST (salt spray test). Left picture is Z600 and right one is hot dip galvanized.

Amount of zinc

If a 10 tonne frame manufactured of 60.3x2 tube has a Z600 coating, it means a 42μm zinc thickness on each side, 650 g zinc mass on a six-metre-long tube and 400 kg total zinc mass. The same 10 tonne frame manufactured with batch hot-dip galvanising has a 75μm zinc thickness on each side, 1200 g zinc mass on a six-metre-long tube and 720 kg total zinc mass.

Environment

Z600 coating is lead free whereas some batch hot-dip galvanising baths include lead and tin as alloying elements, even if they are mostly pure zinc. Less zinc, i.e. thinner coating thickness, means less non-renewable natural resources.

Transportation

Z600-coated tube is ready for use and is normally transported from the tube mill or warehouse to the frame manufacturer. If batch hot-dip galvanising is used, it normally means extra transport to the galvanising plant.

Costs

A galvanised 10 tonne frame contains 400 kg or 1200 kg of zinc mass depending on whether the coating method is Z600 or batch hot-dip galvanised. The price difference between these two options is €1600 at April 2015 prices when only the zinc price is considered.

Appearance

When comparing surface appearance, the Z600 surface is shinier and more homogenous compared with a batch hot-dip galvanised surface, which has a more mattish/topographic look. The occurrence of darker and lighter areas, such as a cellular pattern or some surface unevenness, is allowed. Figure 146 shows examples of Z600 and batch hot-dip galvanised surfaces.
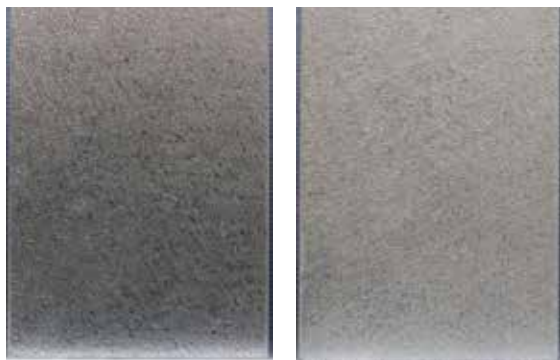

Figure 146. In the left Z600 surface and in the right hot dip galvanized surface.

Welding

When using Z600 tubes it is recommended to remove the zinc prior to welding. Afterwards, the welded area may be protected e.g. with zinc spraying to gain good enough corrosion protection.

Together with batch hot-dip galvanising, welding is done before galvanising and then zinc also protects the weld. Zinc bath size limits the size of welded constructions, so it is probable that final assembly will be done after galvanising with bolt and flanges or a corresponding method. Welded constructions should be designed and manufactured for galvanising, which means e.g. holes for draining excess zinc. These holes are not always practical in terms of aesthetics or structural rigidity. Besides arc welding, other technologies are available for joining pre-galvanised tubes, including arc brazing. Mechanical joining is suitable and may lead to further cost savings, depending on case.

Summary

Choice of the right material depends on, and is a compromise between, corrosion protection, environmental considerations and costs. For very long-term corrosion protection and a frame with a lot of welding, batch hot-dip galvanising is preferable. Z600 coating will give good corrosion protection, environmental benefits and an interesting total price level.

7. Other Fabricating Techniques

7.1 Laser cutting

Laser cutting is a thermal cutting process in which material is cut by a focused laser beam. High-intense energy heats the material to cause melting and vaporisation. Molten material is removed by a cutting gas such as oxygen or nitrogen by using high-pressure gas flow. Oxygen gas is normally used for the cutting of non-alloyed and low-alloyed carbon steels. Oxygen reacts with steel to cause an exothermic-reaction providing more energy for the cutting process. Oxygen results in the cutting edge being coated by an oxide layer, which must be removed before painting, for example. Formation of the oxide layer can be prevented by using nitrogen gas. However, nitrogen cutting is much slower because the material is heated up only by the laser beam.

In laser cutting, beam parameters such as power, energy intensity, focus position and focal length should be adjusted according to the material. Process parameters such as cutting speed, nozzle diameter, focusing, and nozzle distance parameters depend on the material thickness, profile, shapes to be cut and tolerance, as well as edge quality requirements. Material tolerances, optical features, surface quality and flatness have a significant impact on successful laser cutting

Laser cutting quality is generally defined in standard EN-ISO 9013, which applies to laser cuts of thicknesses from 0.5 mm to 40 mm. The geometrical product specifications are applicable if reference to this International Standard is made in drawings or pertinent documents, e.g. delivery conditions. Attention must be given also other customer requirements and special features of tube laser cutting compared to traditional plate laser cutting.

Laser cutting may replace many traditional cutting methods to bring cost savings. The biggest benefits are achieved when cutting complex shapes or different shape types in a tube with demanding dimensional accuracy requirements. Cutting quality and accuracy are excellent compared to other methods using thermal heat, such as plasma cutting.

7.1.1 Tube laser cutting

Tube laser cutting is an application which is used mainly for cutting tubes, as well as beams and profiles using a specially equipped tube laser. A tube laser machine typically consists of a material loading bag or platform, turning spindles to hold the material, a laser cutting cell and unloading area. Because

of many linear, transverse and rotation axes, it is more complicated compared to sheet metal laser cutting. In a fully-automated process, an end component can be completed in one working phase using one tool thus eliminating i.a. sawing, deburring, punching, drilling, mechanical cutting and machining compared to the traditional manufacturing process.

Material shape and dimensional accuracy have a great impact on tube laser cutting. The more accurate the tube, the easier it is to cut and the better surface quality is achieved. Circular precision tubes are the easiest to cut due to lack of discontinuation. However, square, rectangular and flat oval Form precision tubes are also easy to cut because of their excellent dimensional accuracy and good surface quality.

Figure 147. Centred tube by cutting head sensor. A separate measuring probe can also be used for centring.

Tube laser cutting is generally a 3-D process, but normally precision tubes are cut with a 2-D cutting head perpendicular to the surface. The tube or cutting head can move separately or simultaneously during the laser cutting process. However, bigger tube lasers often have a 3-D cutting head, which can be used to bevel angles of up to 45°.

Cutting on curved surfaces

Figure 148 shows the typical characteristics of tube laser cutting which must be taken into account during design and manufacturing. Perpendicular to surface cutting attains a conical hole in a circular tube and corner radius area of a rectangular tube. However, a 2-D cutting head is able to produce a cylindrical hole if the tube and cutting head are moved simultaneously.

A cylindrical hole in the corner area of a rectangular can only be made using a 3-D cutting head.
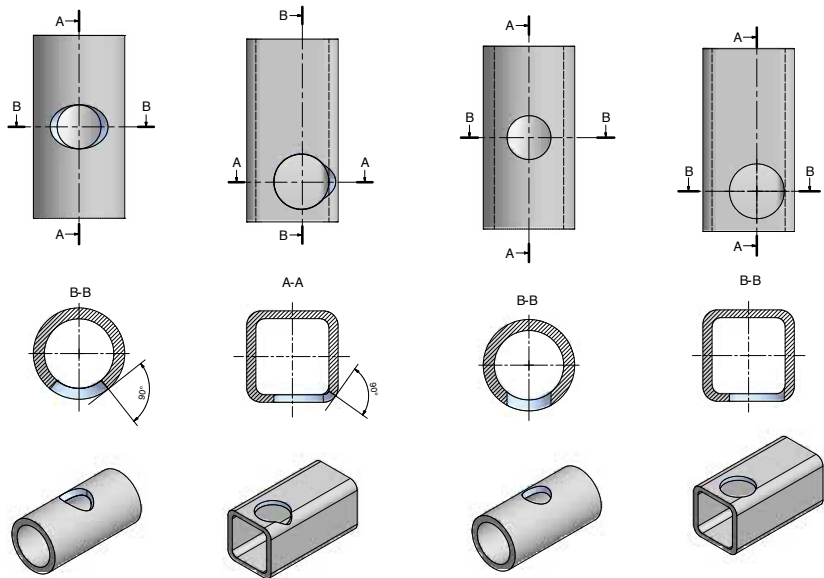

Figure 148. Perpendicular to surface cut (left) for both round and square tubes. Cylindrical holes (right), which will need bevelling features when cut in the radius area on square shaped tubes.

Angle cutting

Tube laser cutting can replace the traditional sawing phase by end forming, straight cutting or angle cutting. Angle edges are normally made by cutting, such as a perpendicular to surface cut, and in any case this way is faster. It is also possible to cut as sharp an edge up to an angle of 45° using a 3-D equipped cutting head.

Bevelling

Bevelling is typically used for some counter holes or any weld preparations. A bevelled surface is ready for a screw head or welding joint in any construction or engineering application. The maximum cutting angle is 45°. A semi-bevel includes the root face and bevel as a result a prepared edge for welding.

Design tips

Tube laser cutting provides many changes to improve productivity or product functionality. A couple of tips for designing laser cutting components are given below.

Drawings should mention the following specifications:
– If the holes are, e.g. galvanising, dewatering, casting or ventilation, without exact tolerance requirements
– If angle cutting such as a sharp edge is needed in the following working stages
– If laser marking or small holes are for the positioning of later drilling
– If a hole is cylindrical or conical. Max. diameter of cylindrical holes is about 60% of the tube diameter.
– Measurements
– Tolerance requirements

Applications

Laser cutting is a highly suitable cutting method to machine any precision tubes. Applications generally include many different holes and end forms to create precision connections with other parts. Typical applications can be found in furniture, sports equipment, automotive parts, lighting structures or any parts including holes, slots and end forming where high quality is required. Laser cutting also results in short lead times and prompt delivery also with higher volumes.
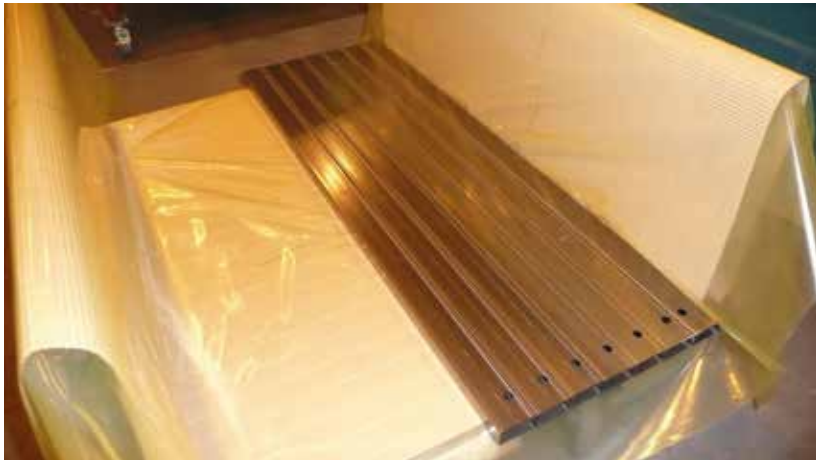

Figure 149. Holes on precision tubes.

Tube fittings

Tube fitting joints can be made "edge-to-edge" or through cutting. High cutting accuracy makes final assembly easier and quick.

Figure 150. High precision tube joining "edge-to-edge" with curved surfaces.

Figure 151. High precision tube joining in the form of through cutting.

Tube laser cutting can provide an innovative approach to the development of products for easy final assembly or functionality. Notch cut laser cutting to ease the bending phase, see Fig 152, and also reduce the need for welding. Frame type structures may reduce the number of items. Laser cutting is a versatile machining method that can provide free shape cutting for e.g. any locking solutions. Taking the advantages of laser cutting into account in product design means shorter product lead times.

Figure 152. Locking geometry for industrial use.

Figure 153. Adjustment geometry in furniture.

7.1.2 Case study: Cost savings in assembly by using laser-cut parts

Figure 154 shows how a product originally made from two parts can be man-ufactured as one part through the innovative use of laser cutting. Notch cuts have been made in the material to one side of a tube, together with accurate holes and ends. After cutting, the part is bent and ready for assembly without the need for many traditional working phases such as sawing, drilling and welding. This innovative processing by laser shortens lead time, which results in cost savings throughout the production process.

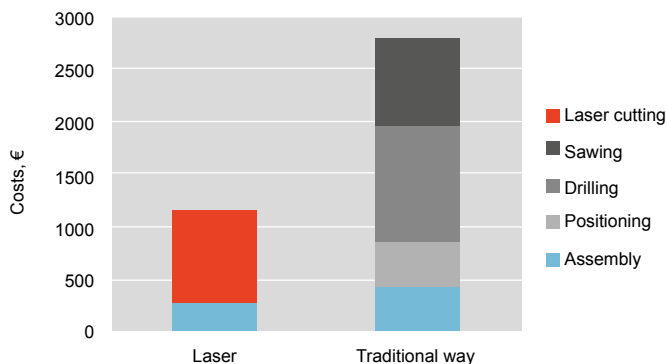**Figure 154.** Frame type structure.

Figure 155. Laser cutting costs [€] compared with the traditional way. Referring to Fig. 154.

Figure 156 shows the quick assembly of three parts fitted with location brackets. In this application, the potential of laser cutting technology was taken into account in the design phase of the parts. The parts are perfectly coherent with each other and suitable for direct assembly, which shortens lead times in parts processing. The dimensional accuracy of laser cutting guarantees higher quality and reduces the possibility of defects, since the parts fit together as required, thus eliminating an extra positioning phase.

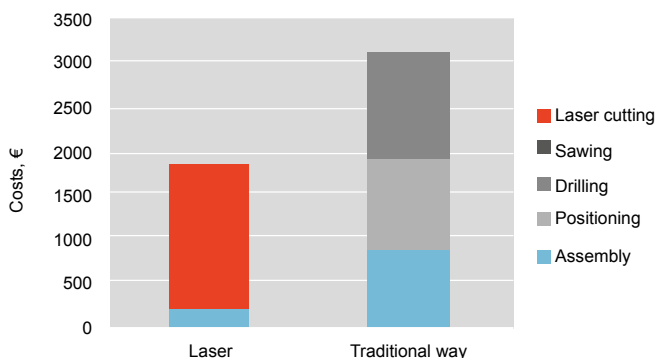**Figure 156.** Location brackets for accurate positioning.

Figure 157. Laser cutting costs [€] compared with the traditional way. Referring to Fig. 156.

7.2 Punching and hole expansion

Punching, aka perforating or piercing, is a quick method for providing precision tubes with different shaped holes of a diameter greater than the material thickness. An even greater variety of shapes and higher quality holes can be achieved by drilling, machining and laser working. However, despite machinery evolution, punching is still very widely used for reasons of cost.

The tools used for punching are specially designed NC machines, eccentric presses or separate punching units. The latter are fast working, manually operated hydraulic or pneumatic cylinders, either with spring-return or two-way movement action. Punching units may also form part of an automatic multi-function tube working machinery or production cell.

The functional principle on NC punching machines involves the positioning of the tube to be punched or the positioning of both the tube (linear transfer) and the punching units (this may replace, for example, the rotation of the tube). Depending on the tooling, one punching unit can make several cuts and with machines comprising several punching units, output rates can be further increased.

The punching tool consists of a punch (skewer) and possibly a blanking die (cushion) located in the mandrel and/or in the die supporting the tube, see Figure 159. The punch is usually made of hardened and ground tool steel and the blanking die made of tool steel or hard metal. It is possible to punch only one tube wall or both opposite tube walls in one stroke.

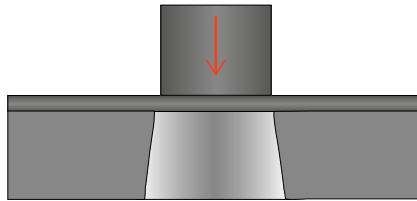**Figure 158.** Punching tooling. Courtesy of Bors Automation and Tool AB.

Figure 159. Principle of punching.

Figure 160 shows the typical geometry of a punched hole edge: first the steel edge is bent (incomplete edge), then the punch will penetrate the material and a shiny cut face is developed (burnished zone) and finally the rest of the cross section is fractured (broken zone). The burnished zone is normally 20–40% of wall thickness.
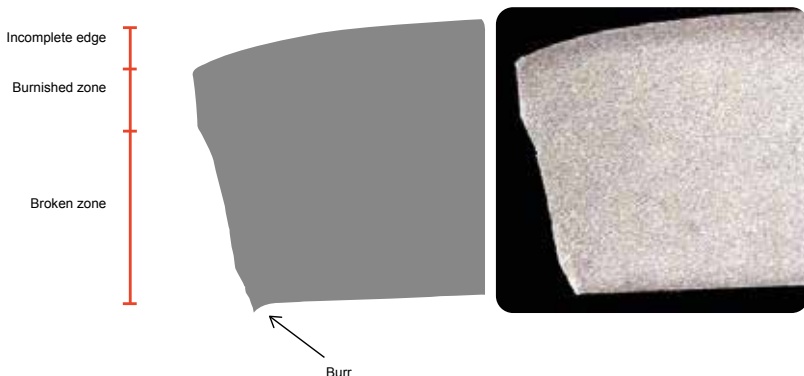

Figure 160. The geometry of a punched hole edge.

Fine punching is a method where the upper punch perforates a hole and the lower punch provides a counterforce to prevent the steel from fracturing. The wall to be cut is also pressed between the pressure plates, see Figure 161. In this way, tight tolerances for a hole can be achieved because the cut edge is almost perpendicular. Also the fractured zone may be omitted, burr high is minimal and need for post-processing may be eliminated.
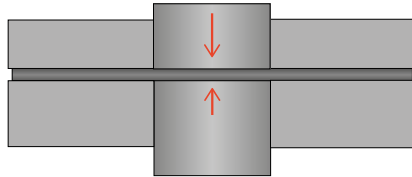

Figure 161. Principle of fine punching.

One wall can be punched with or without a die cushion. When the use of a die cushion is omitted, the hole is punched with a more pronounced indented edge. Deformations can be reduced by using a die cushion mounted on a mandrel inserted into the tube. This is also done when the designer has defined a hole to be located very close to the tube end or a set of holes close to each other.

There are two ways of handling the punching of two walls in one stroke:

- One punch pierces two walls in succession. Punching of the second wall takes place against a die cushion in order to avoid indentions. If the first wall is punched against a die cushion, the mandrel must be provided with a hole to allow the passage of the punch and chip through the second wall.

- Two punches perforate the walls simultaneously without a die cushion. The skewers are mounted on the same headstock. The advantage of this method is that the burrs of both holes remain invisible inside the tube.

Tubes are commonly punched also as flattened, for example, by way of preparing them for screw and rivet connections, see Figure 168.

The intended use and further fabrication dictate the quality requirements on punched holes, such as:

- The tolerance of hole location
- The tolerance on hole dimensions; diameter
- Burrs and hole geometry
- Chip removal; can be promoted by improving the punch shape by grinding
- Deformations of the tube; indentation, flattening and tube flexure

The extent of indention around the hole periphery depends on tube dimensions and hole size. On circular tubes, the indentation is oval. The degrees of deflection and flattening depend mainly on the tools securing the tube. The tendency to deflection and flattening increases proportionately as the number and size of holes increase.

The dimensional accuracy of the punched hole and the surface quality in the cut can be improved by a so-called shaving function. Shaving involves the cutting of an initial hole followed by another punching to remove a narrow zone along the periphery of the hole. The thin chips produced in the process are difficult to remove from the punching machine and may cause jams.

The effect of clearance on burr formation is relatively small but should be considered especially if the part is visible, painted, handled or processed. As plastic deformation is greater in ductile materials, such as SSAB Form Tube 220, than in brittle materials, the former are also likely to develop heavier burrs. Cracks in cut edges reduce the formability of the edge, which is essential if hole will be expanded later. Cracks also decrease the fatigue resistance of the cut edge and may act as initiation place for fatigue breakdown.

The relationship between the burnished and fractured area in the hole edge depends on the tooling clearance, steel grade and steel thickness:
- The smaller the clearance, the larger the burnished zone
- The lower steel the strength, the larger the burnished zone
- The thicker the wall, the larger the burnished zone

A worn out punch will result in increased burr height and force required.

According to current knowledge, the optimal clearance with regard to tool wear and the quality of cut is about 6-12% of wall thickness. With cold rolled steels, a 10% clearance gives the same burr height as 2-3% clearance. As clearance decreases the burnished area increases, but the cutting force and wear will also increase. High-strength steels, such as Docol Tube 590, will allow somewhat greater clearance, about 9-16%. High-strength steels are less sensitive to burr height relative to clearance.

Lubrication, coatings and proper maintenance contribute to the condition and service life of tools. The wearing of cutting edges is considered to be the most important factor that causes burrs. Punch wear results in a higher percentage of incomplete hole edges and burnished area and increases the burr height. The wear of the die cushion is reflected as increased burrs at the hole.

Compared with sheet steel materials, punching of the tube involves factors that contribute to variations in burr height:

- The interface between the two walls of the tube punched
- The effect of punching the first wall and of the chip on punch movement
- The curved surface of circular tubes
- The flattening effect of supports and dogs on the burrs

In normal production, a burr height less than 10-15% of wall thickness is easily achieved, for example, with precision tube steel grades. The location of the weld during punching has no significant effect on burr height or on other quality parameters. In high-volume production, the weld should preferably not be located in the area to be punched because of its wearing effect on the tools due to its higher strength and hardness.

Too large a clearance, see Figure 162, results in:

- Fractures not meeting and a notch is formed
- Large fractured area
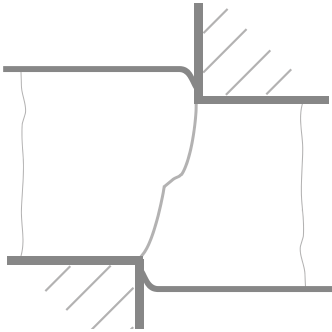- Uneven shear surface
- Large edge bending

Figure 162. Punch clearance too large.

With too small clearance, see Figure 163:

- Large burnished area
- High cutting force and faster tool wear
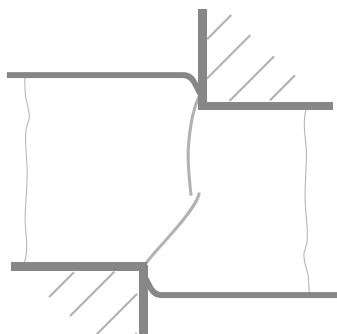- Increased possibility of sticking and punch breakage

Figure 163. Punch clearance too small.

With proper clearance, see Figure 164:
- Adequate fractured and burnished areas
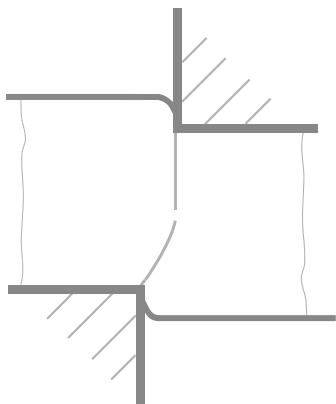- Low cutting force and wear
- Even cut edge

Figure 164. Optimised punch clearance.

In the case of metal coated tubes, it is important to take the burrs into consideration when planning the punching operation. This is because deburring is difficult without damaging the coating and there is an increased risk of losing corrosion protection. Zinc will stick to the punch and the amount of zinc sticking correlates to the zinc thickness on the surface, although the maintenance interval is quite long, see Figure 165. Galvannealed coating is less susceptible to sticking.
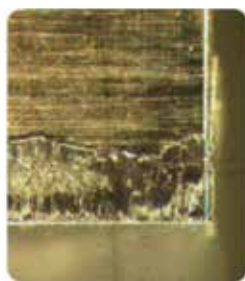
New punch   Used punch

Figure 165. New and used punch edge after piercing galvanised material 13,000 times. Some zinc galling on the punch side is visible.

When punching higher-strength tubes, e.g. Docol Tube 980, the share of the burnished zone decreases and the share of the fractured zone increases, as seen in Figure 166. On the other hand, with lower-strength tubes, e.g. SSAB Form Tube 190, the burnished zone will increase excessively. This clearly indicates the need for clearance adjustment in order to achieve high quality holes.

SSAB Form Tube 190 Z   SSAB Form Tube 220 Z   Docol Tube 980 GI

Figure 166. The effect of a change in shearing for steels of different strength levels. Punching parameters are the same for all materials for benchmarking purposes.

Hole expansion is a process where a hole is stretched to increase its diameter. This is similar to flanging in sheet metal processes. An expanded hole may be used e.g. as a threading for a bolt. The edge condition has a major impact on the hole expansion ratio, see Figure 167. Damage, due to e.g. improper punching clearance, on the hole edge dramatically affects the hole expansion property. There is also a correlation between the work hardening exponent and hole expansion ratio and thus the better the uniform elongation the better the tube hole expansion rate.
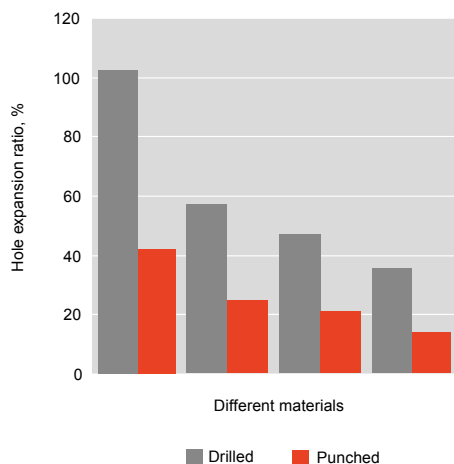
Figure 167. HEL % with different materials, a comparison between punched and drilled holes.

> **PRO TIP:**
> **Punching clearance SSAB Form Tube 220 C:**
> **~5% for a tight clearance**
> **~10% for best edge quality and tool lifetime**

7.3 Flattening

A tube can be flattened either completely or so as to leave a gap of a given width between the tube walls. This gap can also be filled with steel strip to improve structural stiffness. Flattening leaves the tube circumference almost unchanged, while the cross section is given the desired shape.

It is usually the tube end that is flattened, but middle sections can also be flattened. This is done e.g. in connection with punching to provide counter-sunk for the screw heads. Another application is a groove pressed in the middle of the tube to function as one half of slide bearing housing.

Tube can be flattened to innumerable shapes because the power applied to produce the deformation is controlled both in the tranverse and longitudinal direction of tube. The desired shape is achieved by the proper design of plunger and dolly. The purpose of flattening is to produce aesthetic outlines and facilitate the design of screw, rivet, for example, by bending, cutting or embossing.

Figure 168. Flattened tube end. In connection with flattening, the end has been cut and/or punched.

Connections made by flattening are suitable for fastening structural members at the tube end. Such connections may be chosen when the part to be connected to the tube cannot be welded. Rivets or screws can often be replaced by less expensive and neater flattened connections. In cars, for example, the mounting of joints at the ends of windscreen wiper arms is provided by means of embossed spots and grooves stamped along the length of the tube.

Flattening is also used as a test of the formability of the material and weld. Important parameters for the test and, therefore, also for fabrication by flattening are:

- Degree of flattening
- Weld location
- Speed of flattening
- Work piece lubrication

The machines used for flattening are eccentric and hydraulic presses. Adjustable rates for working by hydraulic presses are: length of flattened section, press force and speed of compression. In eccentric presses, the flattened length can be adjusted. The press force and speed of compression change in proportion to the distance of plunger from the lower dead position. Eccentric presses usually lack speed adjustment.

The condition of the tools as well as lubrication used in flattening reflect on surface quality. If the tool designer has left the plunger or dolly edges too sharp, they will cause cuts on the tube material.

When the tube is fully flattened with sufficient compressive force, a permanent deformation that eliminates springback is caused at the fold of the material. That is, by extensive force the material is "killed". Protrusions of weld metal at fold ends in a fully flattened tube end are partly caused by the tendency of the material to squeeze out (less than 1% of material thickness) in the longitudinal direction of the tube and by excess weld metal left inside the

tube. Such protrusions may hamper welding, for example. They can be reproduced by brushing the cut surface before flattening. If, in partial flattening, the gap between tube walls (the shape of the gap) is given a critical dimensional value with close tolerances, it may be necessary to use a mandrel that is inserted into the tube. The length reduction of a flattened tube depends on the geometry of the flattening required.

Two critical stages in the flattening of a tube:

- At the beginning of the flattening, the strain is highest at the contact point between tube and plunger. At the contact point, the external tube surface is exposed to compression stress and the internal surface to tensile stress. If the tube contains an incomplete weld, the weld must be positioned way from contact point in order to prevent cracking. With a complete weld, the problem does not exist.
- In the final stage of flattening, the stress on the tube bends is at its highest. The situation corresponds to the bending of sheet to a small radius. Therefore, successful flattening depends on the bending properties of the tube material.

In flattening, the forming properties of the tube both in the direction of its longitudinal axis and in the vertical direction are utilised. Working is limited by the bendability of the material because it is normally required that the bend be free from reductions in area that impair the surface quality and strength. The requirements on the bendability of steel increase in parallel with wall thickness.

The bendability of tubes made of modern micro-alloyed steel is illustrated in Figure 169. For bendability of tube wall or in other words cold formed sheet material, please see table 37.

Table 37. Indicative minimum bending radii of circular tube wall for some of the steel grades. Note: Tube D/T-ratio affect achievable flattening rate

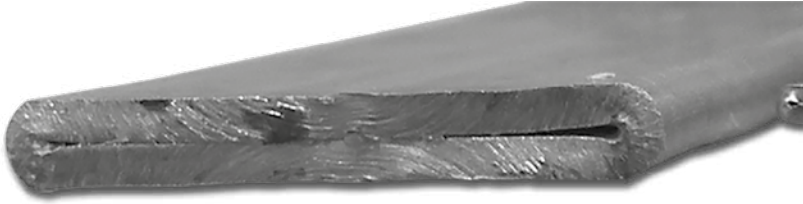| Steel grades in flattening	Minimum outside bending radius [xT]
SSAB Form Tube 190	1
SSAB Form Tube 220	1
SSAB Form Tube 320	1.5
SSAB Form Tube 420	2
SSAB Boron Tube 24 as delivered	2
Docol Tube 590	3
Docol Tube 780	4

Figure 169. Example of the geometry of a straight, fully flattened tube. Note a gap next to a crimp in spite of extreme pressing force. The material of the tube is SSAB Form Tube 220 C.

There is also a flattening test concerning tube quality inspection according to standard EN 10233:1993. The test results can be used for manufacturing process planning for components.

> **PRO TIP: No fully flattening for an advanced high strength tube!**

7.4 Spinning

Longitudinally welded circular precision tubes can be formed by spinning both in the hot and cold condition. For reasons of economy, cold working is more common. The tube is usually worked on its outer surface but inside spinning against a die is possible as well. One of the applications of this method is the fabrication of bicycle wheel hubs. The following is typical of spinning:

- The tube wall thickness changes to the specific measure even when the length of the tube changes
- The tube is pressed against a mandrel or die to the desired shape; the tube rotates or press rolls spin on and around the tube periphery
- The tube undergoes strain hardening
- Good dimensional accuracy
- Surface roughness Ra is between 0.5 and 2µm depending on the tools
- Any material with elongation can be used
- The input tube is required to be of precise geometry

Achievable reduction of wall thickness can be concluded from the reduction of are at failure. Depending on the steel grade, a thickness reduction of up to

70% can be achieved in spinning. For greater thickness reductions, the tube must be annealed between working stages. The minimum reduction of thickness is ca. 15%.

The inner diameter of tubes worked by spinning may vary from about five millimetres to over one metre. Tubes with an inner diameter under 9.5 mm are locked in place during spinning and the tools revolve on and around the tube.

Spinning can be carried out either as counter spinning or forward spinning.

Counter spinning is the faster method but it is not suitable for tubes with weld bead on the inside. The weld causes a strong flexure in a counter spun product. In addition, variations in the tube wall thickness complicate length control of counter spun tubes.

The manufacturing parameters in spinning are: the rate of rotation, feed in the axial direction and feed in radial direction. A thin film of lubricant should be left between the tube and mandrel. Lubrication is also used between rolls and tube, if the highest possible surface quality is required.

The use of longitudinally welded precision tubes for applications involving spinning is limited by weld bead protruding on the inside. Therefore, the tubes for such applications should always be ordered with inside weld planed flush.

7.5 Mechanical joining

Screw and rivet connections have the following advantages:
- Screw connections are easy to undo and the end user can carry out the assembly
- Different materials can be connected
- Painted or otherwise coated members can be joined without damage being done to the coating
- In addition to its retaining function, a rivet can at the same time serve as a knuckle, sleeve, plug, etc.
- The selection of screws and auxiliary parts is wide; for example, the variety of head forms and head covers

Compared with screw connections, rivet connections have the disadvantage of lower stability and fatigue strength. Usually, rivet connections are not water tight or air tight and they cannot be opened without destroying the rivet.

Ordinary rivets can be used on flattened ends of precision tubes. In the design of blind rivet connections for tubes, attention should be paid to the wall thickness of the parts to be connected, the rivet tolerance, the type of load and the expected rates of forces applied, the free hole diameter and the appearance of the connection.

Rivet connections bear shearing stress better than tensile stress. The best retaining effect under vibrating loads is achieved when the free hole diameter is as close to the recommended minimum value as possible. Connections of soft, compressible materials require large-headed rivets.

There are no separate instructions for the calculation of screw or rivet connections to precision tubes. The general practice in the design of screw or rivet connections to precision tubes involves the application of the general rules for structural design, experimental structural design or aware overdimensioning.

The general rules for structural design take the following into consideration:
- Piercability
- Shear failure
- Declination and edge compression
- Tension failure and pull-through tension failure
- Pull-out tension failure

Precision tubes have been tested for the stability of rivet connections against piercing forces. The tests verified that a rivet located in the weld does not weaken the connection.

7.6 Quenching

To create a wear-resistant or ultimate high-strength steel tube, a structural kind of steel tube with ferrite-pearlite or ferrite with a globular carbide microstructure, is converted to fully martensitic by quenching. These hardenable boron steel tubes can be used for applications like cutting tools, lightweight structures or parts having a high energy absorption capacity.

The most common raw material for tube production is SSAB Boron Tube 24 with a carbon content of 0.24% and boron content of 0.003%. This cold-rolled steel grade has a good surface quality compared to hot-rolled materials. In as delivered condition, tubes are well suited for cutting, cold forming

and welding. Welding can be done using all conventional methods. In as delivered condition, tubes may be thermal cut, but a narrow hardened area next to cut will develop.

Table 38. Typical mechanical values of hardened boron steel tube SSAB Boron Tube 24.

Condition	R_p	R_m	A	Hardness
As delivered	470	530	23	
Oil quenched	900	1300	8	
Water quenched	1100	1500	8	HV 470...530

Hardening consists of heating the tube to a temperature of 880-950°C and quenching in water or oil. Cooling is done close to room temperature with a minimum cooling rate of 27°C /s is required. Tempering after quenching is not usually needed because steel behaves in a ductile manner even after quenching due to its low carbon content. Tempering will increase tube toughness though.

Quenched tubes can be welded, but HAZ will become tempered, so hardness and strength will decrease in the area.

PRO TIP: Do you want a springlike tube? Quench a boron steel tube!

8. Transport and storage of tubes

In the storage of precision tubes, the possible risk of corrosion must be taken into consideration. The tubes are normally supplied with light rust protection oil. The oil protects the tube during transport and normal storage. Prolonged storage must be in heated indoor spaces where moisture or the risk of moisture condensation are not present.

Galvanised tubes are easily affected by white rust if moisture gets between the tubes packed in bundles. Therefore, the storage of bundled galvanised tubes requires proper, dry, warehouse spaces.

Precision tubes are products characterised by especially fine surface quality. The surface is very sensitive to scratches and dents. Caution is required with transport and storage; for example, in moving bundles of tubes by forklift.

In storage, heavy loads should not be placed on top of bundles of precision tubes. In order to avoid permanent deformation, care should be taken to provide the tube bundles with sufficient quantities of wood props between the layers.

Tubes are normally delivered in bundles tied with steel straps. If tube with extra high surface quality is required (e.g. tubes to be chromated), the tube bundles may be ordered as protected. In which case, the contact points under and above the bundle are protected by sheet and padding tape is provided under the straps.

9. Precision steel tube properties in a nutshell

Young's modulus E = 210GPa
1MPa = 1N/mm^2 ≈ 0.145 ksi
Poisson's ratio: 0.3

Steel density: 7850 kg/m^3
Steel melting point: 1500°C

Zinc coating thickness: mass of 100g/m^2 = Z100 = 7µm layer per side
Zinc melting point: 420°C
Zinc boiling point: 907°C

Temperature where steel properties are not affected: 200°C

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Precision Steel Tube Handbook – compilation of training material for bending, welding and coating

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