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HFI-welded tubes vs. cold drawn tubes for automotive applications

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Introduction

A main driver for both automotive and general applications is using cost-effective solutions. For tubular applications a high-frequency welded carbon steel tube offers the lowest cost option available in the market. However, this should be balanced with the specific product requirements. These comprise a combination of strength, stiffness and mechanical properties as well as geometrical considerations such as outside and inside diameter, wall thickness and tolerances. Not all of these requirements can be simultaneously met by HFI-welded carbon steel tubes.
Limitations exist for the availability of diameter over wall thickness ratios D/t and attainable tolerances. Also both geometry and mechanical properties of the weld seam area are not always suitable for the designated application.

These considerations are reflected in the current standard for steel tubes for precision applications EN10305[1]. This standard consists of separate parts for seamless cold drawn tubes, welded cold drawn tubes, welded cold sized tubes and seamless cold drawn tubes for hydraulic and pneumatic power systems (plus two additional parts specifically for square and rectangular tubes). The separate parts differ in available diameters, wall thickness and D/t ratios, but also in applicable steel grades.
Tubes for automotive are in general specified based on these standards, where applications with narrow tolerances tend to be presently filled by cold drawn tubes where the tolerances are tighter.

Figure 1. For drive shafts normally cold drawn tubes are used.

With increasing process capabilities in both steel strip and HFI-welded tube manufacturing, the required diameter and gauge tolerances are coming within range of those specified for the cold drawn tubes. This opens the opportunity for cost saving as cold drawing and subsequent heat treatment processing steps are no longer required. Furthermore it enables the application of a much wider range of steel grades such as AHSS and UHSS, the use of which can be tailored to the specific requirements.

General developments in tube mill technology

The cold drawing operation is able to meet its narrow tolerances for both inside and outside diameter based on its specific technology. A welded or seamless tube is drawn over a mandrel, which guarantees the inside diameter, while at the same time the outside diameter is confined by a ring. The concentricity of both operations determines the wall thickness tolerance.
In HFI-tube welding, which starts with flat slit coil, the attainable gauge tolerance is mainly determined by the thickness tolerance of the incoming material. This thickness tolerance is only minimally affected during the forming and shaping of the tube.

Narrow gauge tolerances are beneficial for both tube manufacturers and processors. Processing of narrow tolerance products obviously gives less variation and hence results in a more reliable process. The same holds for HFI-tube making, but additionally it also allows the tube maker to favourably adjust the final wall thickness of the tube.
Steel strip can be ordered with ever more narrow tolerances due to improvements in hot and cold rolling technology in the steel mills. On top of this some tube manufacturers have installed in-line rolling enabling to produce tube with

tailored gauges and improvedtolerances. Apart from potential cost savings this also opened up the market for drawn tubes to HFI-welded tube manufacturers.

In addition to narrow gauge tolerance also accurate diameter tolerance is required. In HFI-tube welding the outside diameter is not defined by a fixed ring, it is mainly the accuracy of the tooling for calibration and final shaping that determines the tolerance. The inside diameter is determined bythe outside diameter and the material thickness. Therefore also the tolerance of the inner diameter depends on the tolerances of outer diameter and material thickness.
The final step in HFI-tube making is often shaping via so called Turk’s heads, a series of non-driven stands. One set can be used to achieve the final diameter using a small reduction and a second set is used to straighten the tube. An additional set before the straightening is a technologically simple and low-cost solutionto improve the diameter tolerance.
To further improve the dimensional tolerance, more accurate axles, bearings and fixtures are required. Several tube mill manufacturers have specialised in these developments and mills using dedicated technology to guarantee narrow outside diameter tolerances are now available.

A further subject in replacing drawn tubes with welded tubes is the weld seam. Apart from mechanical issues also the geometry of the weld can be an obstacle, especially if some fitting needs to be applied. This is reflected by Tube standard EN10305-part 4, as it is especially designed for drawn tubes for hydraulic and pneumatic applications which generally require a smooth bore.
In the HFI-welding process results in excess weld metal on both the inside and outside of the tube. The outside bead can easily be removed by scarfing because this position is readily accessible. In general a smooth surface is obtained, provided the right tooling is applied. The scarfing quality should be monitoredto prevent surface defects. For lacquered or chrome plated applications the surface quality is a strict requirement. These surface irregularities or a longitudinal ‘flat’ stripe on the circumference are emphasized by these surface treatments. However, in general supply of HFI welded tubes for critical surface applications is feasible.

The removal of the weld bead on the inside of the tube is of course more problematic, starting with accessibility. Tooling can only be inserted before the welding point where the strip is not yet fully closed, but obviously has to be applied at a position behind the welding point. Basically the tooling consists of a chisel mounted on a long rod. The issues associated with this are the exact circumferential positioning and applying even pressure in order to minimise variations in the remaining weld seam height. Exact requirements vary depending on application. In general a maximum and minimum weld bead height is specified, typically with a range of 0,2 mm, for example -0/+0,2mm from the wall thickness, and a specific remark that undercutting is not allowed. In other cases the remaining height needs to be minimisedfor applications where the tube needs a tight fit into a different component. In those cases undercutting will result and the wall thickness at the position of the weld seam is reduced (within the given tolerances). For fatigue critical applications special care has to be taken for the smoothness of the scarfed area. A final disadvantage is that feedback on the process can only be given from the end of the mill where the endless tube is cut.

High frequency welding

The obvious difference between a HFI-welded and a cold drawn tube is the weld area. This is of course the case for seamless cold drawn tubes, but welded cold drawn tubes are generally heat treated in the final production step to compensate for the work hardening that occurs in cold drawing.During this heat treatment much of the weld area is fully or partly recrystallized. In a tube that has been normalised (full austenitization) the outside weld seam is hardly visible, if at all. Due to microstructural differences that remain it can still be detected with eddy current.

In the HFI-welding process a high frequency current (typically 400kHz) is induced in the tube and guided preferably along the strip edges to be welded. These edges heat up to almost melting point and are subsequently press welded after which the tube is fast-cooled. This entire process of heating typically takes 0.1 – 0.4 seconds, while water cooling perhaps takes five seconds, all depending on the mill speed. Only a small part of the tubular circumference near the weld is affected by the induced heat, the rest remains well below the transition temperature. This affected area is called heat affected zone (HAZ) and has some distinguishing features and are clearly recognizable.

To minimise the effect of the HAZ the tube can be post weld heat treated. From a microstructural point of view normalisation will be the best choice as the entire circumference of the tube will recrystallize. This will both minimise the effect of work hardening during forming as well as erase the microstructural differences between HAZ and the rest of the tube. However, cost-wise, part of the advantage of applying a HFI-welded tube will be lost. Furthermore, most modern HSLA- and other high strength multi-phase grades are not suited for normalisation treatments. This ability to apply the full range of available high strength steel grades gives a clear advantage of using HFI-welded tubes[2].

Fatigue load

The improved dimensional performance of HFI-tube mills combined with an ever increasing portfolio of available high strength steel grades make the use of HFI-welded tubes, as a cost-effective alternative for cold drawn tubes, ever more interesting.
Potential substitution will not only depend on available tolerances and mechanical properties, also requirements on hardness, specifically that of the weld seam of HFI-welded tubes, are relevant as well. For some applications post-weld treatment has been introduced for this reason.
Another requirement is fatigue performance. Typical cold drawn tube applications for automotive include propulsion shafts and drive shafts which are known to be sensitive to variable loads. The quality of the scarfing and the height mismatch between the weld and the parent material can cause stress raisers which in turn can lead to a reduction in the fatigue performance. Another crucial factor is the role of steel chemistry, especially the Mn/Si-ratio[3], when related to the HFI-seam weld.Similar to flash butt welding HFI welding does not use a filler wire and so it is the tube material itself which is melted and solidified to form the weld.

The investigation into a number of steel grades for fatigue load sensitive applications confirmed the relevance of steel chemistry. Based on required stiffness and strength level a hot rolled HSLA grade was tested and positively confirmed. The same grade, based on similar mechanical properties, but different chemistry didn't pass the test by failing at a low number of cycles along the centre line of the weld. The initially tested grade had a Mn/Si = 17, the second grade Mn/Si = 98. Interestingly the chemistry of the second was introduced to overcome an entirely different problem, i.e. a reduction of the Si-level to get rid of so-called tiger stripes in surface applications.

The reasons behind this are that when the Mn/Si-ratio is low (<4) there are more SiO_2 inclusions which can form pin-holes in the weld zone. In case of a high Mn/Si-ratio (>23) there is a large chance that an oxide film will form between the two sides which remains in the centre line of the weld.. When the ratio is in the range 4<Mn/Si<23, the melting point of MnO and SiO_2 is lower, therefore the viscosity is lower and the oxide film is more easily pushed out to the side of the weld zone. For Mn/Si > 23 however, remains of the oxide film stay in the weld area whichcan easily initiate fatigue cracks

Mn/Si-ratio [-]	Equivalent stress [Mpa]
40	352
43	349
79	234
98	200

Table 1. Equivalent stress **for 100,000 cycles to failure for four tubes with different Mn/Si-ratio.**

Table 1 shows an overview of additional fatigue tests carried out using tubes with several diameters and gauges and steel grades with different Mn/Si-ratios. To enable comparison the equivalent stress for failure at 100,000 cycles was calculated. A clear influence of the Mn/Si-ratio could be seen. As the test programme is still running final conclusions cannot be made, but the results up till now suggest the border between a favourable and unfavourable ratio might not be as strict as originally assumed.

Hardness

With respect to fatigue crack resistance an additional worry might be differences in hardness over the HFI-weld. Figure 1 displays the results of HV0.5-measurements on two different steel grades (Table 2).

	C	Mn	P	S	Si
S1	211	610	16	1.9	221
S2	55	1376	9	5	13

Table 2. Composition in 0.1% of two tested steel grades

S1 is a typical carbon grade and shows a small hardness peak over the weld centre line (*width*); S2 is HSLA-grade and does not show significant variations over the weld seam. Due to the lower carbon content the phase transformations during welding have less influence on the final hardness.

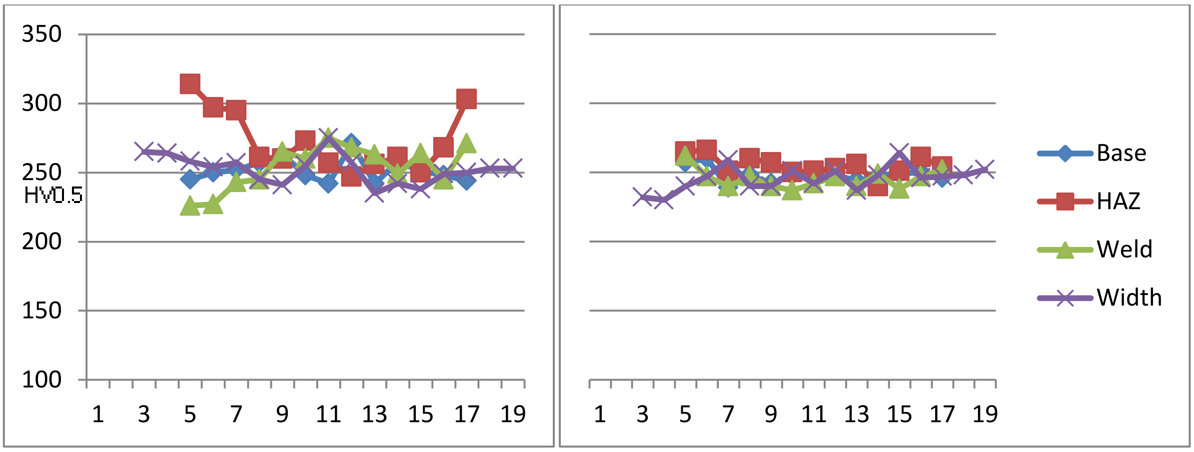

Figure 2. Hardness HV 0.5 of samples S1 and S2. Measurement positions are given in Figure 2.

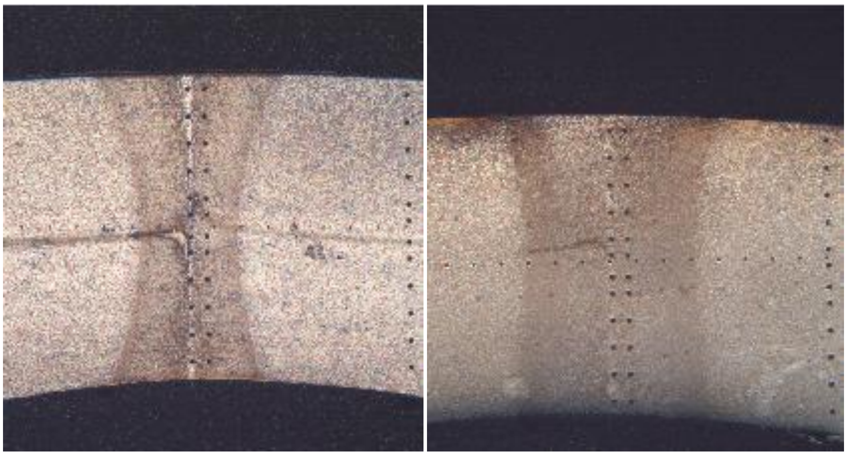

Figure 3. Measurement points for hardness HV0.5 on samples S1 and S1.

Application of high strength steel grades in HFI-welded tubes

One of the advantages of HFI-welded tubes is a wide range of low carbon steels can cost-effectively be applied. There are no fundamental limitations in welding either highly formable grades such as cold rolled DC06 or advanced and ultra-high strength steels (AHSS resp. UHSS), for instance HDT760C (CP800). In the 2016 issue of the EN10305 for welded cold sized tubes the highest grade available has been upgraded from E420 to E700 (based on yield strength) and will in the future doubtlessly be further enhanced. Of course the standard does not limit the availability of higher grades.

Apart from the issues discussed earlier and which primarily deal with structural effects in the HAZ care has to be taken of the resulting mechanical properties after tube manufacturing. As in forming the tubular shape stress and strain is applied the material work hardens and the mechanical properties will change. This has to be taken into account in specifying the steel grade for the tubular application. Figure 3 gives a typical example for grade HC340LA how yield $R_{p0.2}$, tensile R_m and elongation A change as a function of the D/t-ratio.

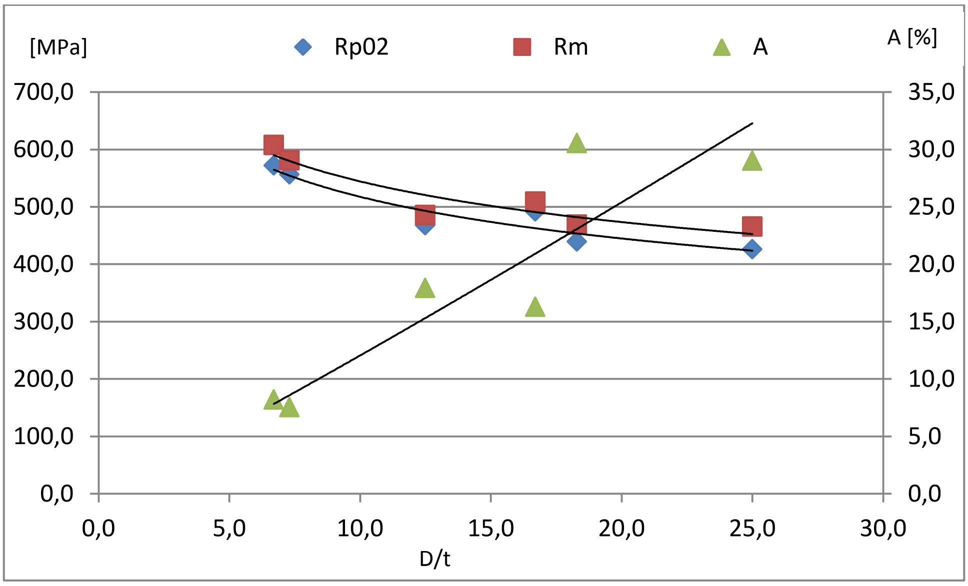

Figure 4. Yield point $R_{p0.2}$, tensile R_m and elongation A as a function of the D/t-ratio for HC340LA in HFI-welded tube manufacturing.

This effect can be both an advantage and a disadvantage. As Figure 3 shows it is possible to use a relatively light grade to attain high tensile strengths, in this case a HC340LA grade to realise a tensile of approximately 600 MPa. The obvious downside is loss of formability as demonstrated by the elongation.
Optimising forming and calibration can significantly reduce work hardening and result in better formable tubes. This is already applied in dedicated mill technology and used for critical applications. But even with optimised forming HFI-welded tubes with similar properties as strip steel cannot be produced direct from the tube mill. This would require an additional heat treatment of the tube differently from the standard normalising (+N) for these high strength grades. Developments for a cost-effective solution in this direction are currently carried out.

Conclusions

Developments in tube manufacturing based on both mill technologies as available steel grades make substitution of cold drawn tubes by HFI-welded tubes for a number of applications not only a viable option, but an interesting choice. Cost saving is an obvious advantage based on a leaner manufacturing process. Furthermore the application of advanced AHSS and UHSS steels enables improved engineering opportunities for weight saving.
A number of the perceived disadvantages for HFI-welded tubes have been demonstrated not always to be valid. Nevertheless will cold drawn tubes remain to be the preferred choice were distinctive properties are required, such as small D/t-ratios, a narrowly tolerated wall thickness and/or inside diameter, or a smooth bore. It is up to the specifier to be aware of the full range of possibilities and – together with the supplier – make the best and most cost efficient choice from the available options.

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[1] EN10305:2016 Steel tubes for precision applications – Technical delivery conditions

[2] L. Berthou, M. Cornelissen, R. Flipsen (2017) Future tubes for axles. SCT2017

[3] M. Shinozaki, T. Kato, T. Irie, H. Hashimoto (1982) Effects of chemical composition and structure of hot rolled high strength steel sheets on the formability of flash butt welded joints. Kawasaki Steel Technical Report No. 6 September 1982.