The use of structural steel hollow sections (from welded tubes) are becoming prevalent in modern steel building construction. Available in both hot-finished and cold-formed finished sections they possess good base mechanical properties, structural behaviour and, architecturally, can provide better aesthetics when compared to other structural sections. Widely available in square, rectangular and round formats, typical minimum yield strengths of 355MPa and 420MPa are easily available for hot-finished and cold-formed sections respectively.

Due to their high degree of structural versatility and affording better strength-to-weight ratio than comparable structural products, the construction sector has started to demand for more complex shapes, tighter radius corners, higher strengths and/or thicker walls, greater low temperature toughness (CVNs), improved bucking resistance and even better fire design performance. This paper aims to highlight some of the recent advances that are being made by steel and welded hollow sections producers to address some of these market demands. In particular, attention is given to the growing importance of higher strength micro-alloyed steels, the metallurgical benefits afforded to meet these challenges and their role in both hot-finished and cold-formed finished sections.

Attention is also briefly given to the economic consideration presented to structural engineers in selecting hot-finished versus cold-formed finished sections. The paper concludes by presenting some potential metallurgical options to further meet future market requirements, specifically for improved fire design performance.

Keywords: Steel, Sections, Hollow, Micro-alloyed, High Strength, Toughness, Fire Design.

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1.0 INTRODUCTION

High strength structural steels ≥420MPa yield strength are today widely used in the construction of tall buildings, large civil and infrastructure projects. The growing availability of both high strength steel plates and sections with a breadth of thicknesses and size has meant that structural engineers have been able to capitalise on significant weight savings as well as designing cost effective solutions. This has allowed a greater degree of architectural freedom enabling increased floor-to-ceiling heights, greater
floor space areas and longer spans to name a few. With this in mind structural engineers are now looking towards higher strength hot finished and cold formed hollow sections with greater performance in order to capitalise on the known weight and cost reductions from conventional structural shapes and fabricated built-up sections. Due to their high degree of structural versatility and affording better strength-to-weight ratio than comparable structural products, the construction sector has started to demand for more complex shapes, tighter radius corners, higher strengths and/or thicker walls, greater low temperature toughness (CVNs), improved bucking resistance and even better fire design performance.

The focus of this paper is on welded hollow structural sections made from as-hot rolled strip steel coils. It aims to highlight some of the recent advances that are being made by steel and welded hollow sections producers to address some of these market demands. In particular, attention is given to the growing importance of higher strength micro-alloyed steels, the metallurgical benefits afforded to meet these challenges and their role in both hot-finished and cold-formed finished sections.

Attention is also briefly given to the economic consideration presented to structural engineers in selecting hot-finished versus cold-formed finished sections. The paper concludes by presenting some potential metallurgical options to further meet future market requirements, specifically for improved fire design performance.

2.0 HOLLOW STRUCTURAL SECTIONS (HSS) IN USE

In many cases today, HSS are extremely versatile and can be used in a variety of structural applications. In particular, circular hollow sections are especially favourable to resist wind loadings because of their low drag coefficients. They combine excellent structural properties with an architecturally attractive shapes. For indication, some examples are given in figure 1. In addition, the hollow interior can also be filled with concrete or other materials to utilise composite action to form a stronger member, as well as increasing its durability under fire conditions.

Figure 1 – End applications of hollow structural sections (Source: International Metallurgy Ltd)
3.0 STRUCTURAL ENGINEERING ADVANTAGE
As hollow sections have gained in popularity, structural specifications have also been amended and continue to be to reflect this. For example, the inclusion of a hollow structural section connection chapter in the AISC specification (360) and design recommendation published in the AISC Steel Design Guide No.24, HSS Connections and the ECS Code have certainly factored into the growing demand and use of hollow structural sections.

From a structural engineering perspective, hollow structural sections can be considered as a very efficient section due to a combination of their inherent shape and engineering, and thus material, properties. The closed shape and relatively large moment of inertia about the weak axis make them highly resistant against torsional and lateral-torsional load. They are particularly well suited for axial compression members that have similar unbraced lengths in both directions. Consequently, they are often used as columns and framing elements that are subject to flexure loads.

Hot Finished versus Cold Formed
Besides the obvious differences in manufacturing routes, it is important to understand the different properties of hot finished and cold formed hollow sections. The selection of which type will govern how and where it can be used according to well prescribed design rules and calculations. For example, figure 2 (from Eurocode 3) highlights that for square or rectangular hollow sections, with respect to the buckling stress used for the calculation, hot finished sections have a 12 to 25% higher flexure curve potential than corresponding cold finished sections.

![Figure 2. Flexure curves for hot-finished and cold-form HSS (Ref: EC3)](image)

4.0 MANUFACTURING ROUTE OF HOLLOW STRUCTURAL STEELS
The production of Electric Resistance Welded (ERW) or High Frequency Induction (HFI) Welded tubes for structural hollows is typically carried out in a continuous forming and longitudinal welding operation [1] that is identical in the first stage when making of tubes for oil and gas pipelines. The difference between the two end products is that once formed into a tube, structural hollows are either cold-formed into the final shape (round, square, rectangle or elliptical) or heat-treated (normalised) and finished into the desired final shape. In some facilities tubes are not heat-treated to high
normalising temperatures and are instead ‘warm’ formed. In this paper, for hot-finished hollows, the focus will be on the full body normalised route.

The most common welding process in the manufacture of the initial tube is via HFI welding. A major advantage is the high productivity attainable due to the high welding velocities inherent with the HFI process. The pipe diameter depends on the strip width and very tight tolerances apply. In order to obtain a continuous strip feed, typically the transverse edge of the as-hot rolled coil is welded to the other. This runs into a coil accumulator and the continuous strip edge milled and then is formed in several rolling stands to a circular shape. The longitudinal strip edges are heated electrically and pressed together to achieve binding.

Two kinds of electrical welding can be distinguished: low frequency welding in the range between 50 to 400Hz and high frequency welding from 150,000 to 500,000Hz. High frequency welding can be performed as a conduction or an induction process. In the conduction process the electrodes are in contact with the future pipe. The current flows from one electrode to the other using the skin effect. The same welding occurs at the induction process but the current transmission takes place without a contact. This is carried out using a ring inductor. The longitudinal weld can be annealed and controlled cooled (water or air cooling) after welding, or in the case of hot-finished, is full body annealed prior to forming into the final shape. An outline of the two process routes is shown in figure 3 [2].

![Figure 3. Schematic showing process routes for hot-finished and cold-formed HSS [2]](image)

5.0 DIVERSITY OF HOLLOW STRUCTURAL STEELS
In a recent study investigating the production standards for cold-formed hollow structural sections [3] it was found that structural tubes for steel construction are manufactured in diverse locations around the world, to a variety of standards, by either
a hot-finishing or seamless process or, more commonly, by cold-forming. The results highlighted problems regarding surface finish and corner cracking with certain cold-formed square and rectangular hollow sections. Together with other studies such findings, for example, have led to a fundamental re-appraisal of the cold-formed manufacturing specification in North America.

It was concluded that the manufacturing methods for these products were different and this also extends to hot-finished sections where 'hot-finished' stands for a manufacturing method where the final forming process of the tube is carried out hot, with final deformation >700°C, or where the tube is cold-formed and then subsequently full body heat-treated at a temperature >550°C. Normalised and normalised rolled tubes are regarded as hot-finished provided the tubes are processed or heat-treated in the normalising temperature range (i.e. in the austenite microstructure).

Consequently, this implies that the material selection of the as-hot rolled strip is even more critical for a quality final structural hollow section whether it be hot-formed or cold-finished and even more so in the case of higher strength steels. The following sections aim to highlight the benefits, and thus advantages, which are conferred when niobium is chosen as the principal micro-alloying element in the production of high strength strip steel for high strength structural hollow sections with demanding performance requirements. As the basic metallurgical function of niobium as a grain refiner and precipitation strengthening element is well understood and several leading papers are widely available in the literature for reference this will not be discussed in detail. Instead focus will be given to the advantages that micro-alloying with niobium provides.

**6.0 HIGH STRENGTH STRUCTURAL STEELS**

As highlighted earlier, structural engineers are requesting for thicker and/or higher strength hollow sections. It is well understood that unless the steel alloy design (i.e. chemical composition) is suitably enriched, increasing the strip thickness will mean lower final strengths. One of the simplest routes to achieving this is by increasing the carbon and manganese contents, however, adopting this strategy will not only lead to greater risks of failure when welding (on-site) by the consumer due to increased carbon-equivalent values (CEV or CE), it also leads to lower elongations (i.e. ductility). Furthermore, the higher carbon content will also lead to poor low temperature toughness properties (CVN) due to a greater degree of pearlite within the steel microstructure. From a manufacturing point of view, lower ductility may lead to corner cracking (micro) during cold forming and also potentially poor performance of the weld line in the hollow section if the coil is slit due to greater levels of centre line and mid-coil carbon segregation.

Consequently, steelmakers must look at other alloying concepts to better meet final end-user requirements and more importantly, to be able to manufacture both hot finished and cold formed hollows. Fortunately, due to similar manufacturing methods and demanding end user requirements a lead can be taken from automotive steel developments where novel micro-alloying concepts have been successfully applied for structural components for heavy commercial and yellow goods off-road vehicles.
When targeting yield strengths from 460 to 700MPa (65 to 100ksi) a combination of metallurgical strengthening mechanisms must be engaged, as highlighted in Figure 4 [4]. Here it can be seen that in order to develop higher strengths (and thicker) one has to move from standard solid solution hardening elements into finer grained ferritic steels, greater levels of precipitation strengthening with more reliance of a bainitic / acicular ferrite microstructure (both microstructures having a greater degree of dislocation hardening). However, in designing the correct steel microstructure (and thus strengthening mechanism) consideration must also be given to the actual process route experienced by the as-hot rolled strip steel when making either a hot finished or cold formed hollow section.

![Figure 4. Contribution of various strengthening mechanisms via alloying to achieve up to 700MPa yield strength in hot strip [4]](image)

The vast majority of automotive and ERW linepipe produced today keep the carbon content below 0.12%, primarily to have better low temperature toughness, to avoid the peritectic region during slab casting and solidification and consequently minimise any macro segregation effect (or in some case just above the peritectic at 0.15%C). Therefore, to develop higher strengths small additions of micro-alloying elements of niobium and/or vanadium are usually applied from 0.025 through to 0.10wt.% depending on the final strength, thickness and specification.

### 6.1 Improved consistency of final mechanical properties

Whilst the rolling of plain carbon steels is a relatively straightforward task, rolling of High Strength Low Alloy (HSLA) is more challenging. This becomes of particular important when hot rolled coils are slit into two, three or even four pieces when making hollow sections. Therefore, for any slit coil it is crucial that the as-hot rolled coil maintains a good degree of consistency in mechanical properties both along and across the entire length and width of the coil.

As outlined above, lowering of the carbon content <0.12%C will help minimise any likely macro segregation effect, although it is acknowledged that often working just above the peritectic region at 0.15%C is also popular. In any case, for higher strength steels the main three strengthening components are grain size, precipitation and dislocation strengthening – all contributing towards the final mechanical properties. Therefore, it is important that when hot rolling these steels not only is the correct alloy
design chosen but the optimum-processing conditions are applied in order to minimise any inconsistencies.

Uniform grain size
Firstly, a fine and narrow grain size is preferable and alloying with sub-stoichometric additions of titanium (approx. Ti/N ratio of 2.2 to 3.0) will not only aid a uniform as-reheated grain size during slab reheating/soaking but these fine TiN precipitates will also help control the grain size in the Heat Affected Zone (HAZ) and accompanying inter-critically reheated zones when sections are welded on-site. A fine and homogenous starting austenite microstructure is beneficial to ensure that there are no bi-modal grain sizes developed during reheating resulting in a mixed grain size in the final steel which will be detrimental to the notch toughness. In order to refine the microstructure (and thus impart higher strengths and better notch toughness – Hall Petch relationship) small additions (0.020 to 0.050%Nb) of niobium are applied to purposefully hot-roll below the recrystallisation temperature, i.e. the well-established practise of TM (Thermo-Mechanical) rolling. Although not discussed in detail here, it is important to note that niobium is widely regarded as the only micro-alloy which can cost effectively and efficiently achieve this.

Balanced precipitation strengthening
The other main strengthening mechanisms are precipitation and dislocation strengthening. The latter is more attributed to lower temperature transformation microstructures which are commonly derived by cooling the as-hot rolled strip steel to low coiling temperatures below 550°C and the resultant bainitic microstructures are often not desirable for hot-finished hollows that are heat-treated. Moreover, at such low coiling temperatures the mechanism of precipitation strengthening (the other main strengthening component) is very sluggish due to the low temperatures and therefore will not generate the appropriate strengthening contribution for the cold-formed hollows. This is highlighted in figure 5.

![Figure 5. Influence of coiling temperature on precipitation strengthening.](image)

Therefore, if the mechanism of precipitation strengthening is to be relied upon to generate the additional 'uplift' to the strength then the correct coiling temperature has
to be reached. It is important to remember that at this stage of processing the role of niobium is similar to that of vanadium as a result, often, both elements are used in tandem although the advantage of niobium is that only half the amount is required to generate the same strengthening contribution (see figure 6). In any case, metallurgically at this stage the amount of precipitation strengthening is largely governed by the coiling temperature and also the temperature profile of the coil as it cools.

![Figure 6. Yield strength increase by precipitation (dispersion) strengthening of 0.01 to 0.50%C steel (1,300ºC soaking, isothermal precipitation at 600ºC to maximum strength increase)](image)

Consequently, this can result in a high variability of mechanical properties especially if a vanadium only microalloy is used (as vanadium’s main strengthening contribution is imparted only at this stage of the process). This is in contrast to niobium, which as described earlier, also contributes to strength by refining the ferrite grain size (and help homogenise the parent austenite grains) and so the degree of variability from dispersion strengthening will be less. For structural engineers this is an important issue as a higher variability in properties coupled with inherent residual stresses within the final cold-formed hollow section which could lead to local buckling at low post-yield strains [5]. Therefore, the thermal history of the steel through production must be understood in detail, as is has a direct effect of the final mechanical properties of the product.

As highlighted, one area of processing which is of particular interest is the coil cooling. This has been identified as a significant source of temperature variations and has therefore been the focus of much research work as the final part of the rolling process the properties of the steel are likely to be set here. The proximity of the coil cooling area to the run-out table also gives an opportunity to adjust the temperature of the coil when it is coiled. On removal from the coiler, the coil will cool very slowly to room temperature. However, during the cool there will be a tendency for precipitate ripening to mirror the cooling profile of the coil. This is observed from figure 7, which shows the topological yield strength developed from a section of a niobium HSLA strip steel [6]. This particular steel coil exhibits softer strengths at the edges, suggesting that insufficient time at temperature was experienced to generate optimum secondary hardening from Nb(CN) particles, unlike the mid-width of the coil that appears to have
experienced the right cooling conditions. It is factors such as these that will also impart some degree of inconsistency within the coil.

![Topological yield strength distribution for a niobium HSLA strip steel [6]](image)

In general, it has been found, for high micro-alloyed steels (niobium or vanadium), that the immediate coil ends will exhibit higher strengths than the body due to exposure related effects of the inner and outer laps [7-8]. However, if the steel is solely microalloyed with vanadium only, i.e. overly relying on precipitation strengthening rather than a combination of grain refinement and precipitation strengthening, then the final mechanical properties inconsistencies will be further impaired.

This is shown quantitatively in figure 8, where two cooling curves representing distinct parts of the coil are superimposed onto iso-hardness curves of a steel with 0.02% niobium in solid solution obtained for various annealing times and temperature conditions in the ferrite [8]. The difference hardness increases at a certain annealing temperature is a result of the annealing time correlating with the volume fraction and particle size of the ferrite precipitates. As after a certain time, fine NbC precipitates are formed homogeneously throughout the matrix. With longer annealing times the amount of such precipitates increases and a hardness of up to 30HV (corresponding to 100MPa tensile strength) can be realised. With increased annealing times, the hardness is expected to fall due to particle coarsening effects. This is something that is inherent to all hot-rolled coils. Although it is important to note that if the applied coiling temperature is well below the desired optimum, then the reverse will be true; i.e. the coil ends will be soft due to suppression of precipitation.

Also, a change in the second phase micro-constituent and volume fraction must also not be forgotten. To minimise this effect, and depending upon the response time of the run-out-table control system, it is possible to apply a catenary or U-pattern cool to the strip. The process involves a reduction in the level of cooling applied at the head and tail end of the hot-rolled strip and thus producing a coil with hotter ends. This will, to a degree, counteract the rapid cooling experienced by the exposed outer and inner laps and thereby balance the overall coil cooling rate. Figure 7 earlier highlighted that with the correct set-up the variation along the length and across the width of the coil can be significantly minimized to 25MPa, which is excellent and way below the standard 60MPa tolerance level set by many automotive manufactures.
Figure 8. Iso-hardness curves as a result of precipitation hardening by NbC for a 0.02% Nb steel with different coiling temperatures [8].

Figure 9 highlights the optimum balance that can be achieved between fine grain sizes and precipitation strengthening contribution for a range of lower carbon niobium microalloyed steels for yield strengths from 300 to 500 MPa (minimum) [6].

Figure 9. Contribution of various strengthening mechanisms on the strength of range of niobium micro-alloyed hot rolled strip steels [6].
Lastly, and often overlooked, during cooling and coiling the strip steel can still be undergoing phase transformation and therefore the latent heat evolved in transformation process must also be considered [9]. Although the cooling rate of the coil will somewhat depend on the coil weight and dimension (including strip thickness), its positioning in the cooling area (eye to the sky or horizontal) should also not be overlooked when considering the uniformity (consistency) of final mechanical properties.

6.2 Finer final grain size tighter cold finished radii

During cold-forming (i.e. deformation) of structural hollows and in particular for square and rectangular sections, strain is highly localised at the corners and it is here where the residual stresses are the greatest. It is also the area were micro-cracks are likely to form and thus initiation a crack. Depending on the microstructure of the steel, propagation of this crack will be largely dominated by the interface of different phases. Due to the combination of soft ferrite and any harder present second phase, the deformation is only concentrated in the ferrite leading to delamination or micro-cracks at the ferrite-harder second phase boundary. Such in-situ induced micro damage can quickly turn into a propagating crack along the interface, especially if the harder second phase is found in a banded formation.

Whilst all steel suppliers and hollow section manufacturers strive to avoid this happening, practically, the development of a finer grain size (via niobium microalloying) coupled with a finer size and distribution of harder second phase microstructure should result in a tighter bending angle. As shown in figure 10 for a dual-phase steel design from an automotive cold-formed section [9] which applied a small addition of niobium to develop a finer overall microstructure. The result shows a tighter bending radii which theoretically would allow a cold-formed or warm-finished to have tighter radii and thus make them more like the corners found in hot-finished hollow sections (and thus increase their moment of inertia and elastic modulus).

![Figure 10. Improvement of bendability of an automotive DP780 steel grade by niobium microalloying [9]](image-url)
6.3 Improved low temperature performance
In hot-finished (fully normalised) hollow sections, due to the heat-treatment process applied to the entire section, the final microstructure is very homogeneous and uniformly distributed. Consequently, the low temperature toughness is not impaired from the parent as-received strip, the flat face and the hot corner. In contrast for cold-formed hollow sections, the work-hardening (deformation) experienced at the cold corner results in reduced low temperature toughness performance. This is highlighted in figure 11 [10] and is well known. Extensive investigations have been conducted on the effect of cold forming of the toughness of hollow structural sections which have shaped the current rules for the selection of European hollows for overall notch-toughness [11]. Nevertheless, it is important to also recognise that different cold forming methods will also have an influence on the final impact properties.

![Figure 11 – Typical impact property trends for hot-finished and cold-formed HSS [11]](image)

However, if a finer grained steel is applied due to microalloying with niobium (grain refiner) then not only will the parent strip and cold flat face have better low temperature toughness performance but the cold corner capability to absorb energy will also improve in a similar fashion (as highlighted in Figure 11).

6.4 Fatigue
The applicability of cold formed hollow sections is sometimes questioned or limited because of concerns regarding poor fatigue behaviour in the corner areas due to higher levels of residual stress and thus hot finished sections are sometimes preferred. However, research undertaken comparing cold and hot finished hollows has shown that there are no major differences in dictating the fatigue strength of the two types of materials [12]. Moreover, the fundamental reasons are related to geometrical factors and soundness of the surface and therefore moving to higher strength steels is unlikely to change this observation.

7.0 ECONOMIC ADVANTAGES
Economic and environmental constraints favour cost competitiveness and higher strength, as has been demonstrated in the wider literature with the application of high
strength structural plate, as rolled beams and built-up sections, and a similar principle applies to the use of higher strength structural hollow sections. In essence, the higher the strength, the lighter the section.

When selecting which structural component to use, it is clear from the market that the unit material cost of hollow sections is higher than that of open cross sections. However, the structural performance of the hollow can permit a lighter design, in some applications. Two examples in the AISC Design Guide 24: Hollow Structural Section Connections compare W-shape and hollow structural section (HSS) compression members with similar load capacities. For a W8×31, which is 8-inches. deep and has an 8-inch wide angle, the comparable round HSS 7.50x0.375 is 8% lighter while HSS8x8 is 17% lighter. Similarly, a W14×109 is comparable in size and capacity to the round HSS14.00x0.625 and HSS14x14, but for both the HSS is 18% lighter [13]. As found with open sections, reducing the weight also saves in transportation and erection costs [14]. In those applications where paint or fire-proofing is required, the fact that HSS has up to a third less surface area than comparable W-shapes can result in using less material and reducing application time, both of which reduce costs. Furthermore, the surfaces are relatively easy to clean and the lack of protruding corners reduces susceptibility to corrosion [13].

Overall, the cold-forming route is naturally economical, it accounts for over 75% of the market and can mostly adapt to higher strength, too. The applicability of cold-formed tubes is sometimes questioned or limited due to doubts about its low-temperature ductility, the deformation capacity of welded joints, suitability for welding in the cold-formed corner and poor fatigue behaviour. It is also claimed that choosing hot-finished tubes means it is possible to avoid the above risks because these products have inherently better grain structure and superior mechanical properties compared with their cold-formed counterparts. In other words, there are claims that cold-formed tubes do not offer an acceptable level of structural safety and reliability, however, there are significant published reports and investigations undertaken buy respected bodies such as the AISC and CIDECT that show that this is not necessarily the case.

Nevertheless, the observations presented in a recent paper [15] investigating the performance of hollow sections from different sources found that they exhibited a ‘diversity of quality and thus also a wide scatter in their structural performance’. They concluded that the manufacturing method, hot-finished or cold-formed, is not the fundamental factor dictating the properties of hollow sections. The basic reason is related to other factors in steelmaking and tube manufacturing. Therefore, selection the correct as-hot rolled strip with uniform and consistent mechanical properties is a good start as any and where higher strengths are being considered, then those produced using niobium as the principle microalloy should be given first consideration.

8.0 FUTURE – fire resistance hollow structural sections?
Studies have shown that the reduction in product properties between cold-formed and hot-finished sections under fire loading is small, and hence there is no differentiation between the two product types in according to the EN 1993-1-2 rules for structural fire design [16]. The study also highlighted that according to EN 1993-1-2 and EN 1994-1-2 under fire loading hot-finished and cold-formed hollow sections, both unfilled and concrete filled, have equal buckling resistances. In fire designs cold-formed and hot-
finished perform equally, but the use of cold-formed hollow sections meant a lower cost. Nevertheless, as most internally exposed steel structures, in particular for the built environment, are likely to require a degree of expensive fire-prevention measures (i.e. intumescent coatings) the development of a fire-resistant parent strip steel would be incredibly cost-effective to reduce the thickness of the applied coating system.

Once again, the benefits in the synergistic behaviour of niobium with molybdenum in maintaining strength at temperature is reasonably well understood from research undertaken in 1990’s, and has been applied as ‘fire resistant steels for building applications’ for plate, open sections and tubes [17]. These commercial products have largely been applied in Japan and the maximum yield strengths are ≤350MPa, therefore future opportunities exist with steelmakers to advance the strength levels towards 420 and 460MPa yield strengths through the right combination of niobium, molybdenum and other suitable elements to develop the optimum precipitate and corresponding steel microstructures (not an implausible undertaking). However, structural engineers must also recognise the value and demand such future market products.

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