China Steel Rebar: Market Overview and Latest Product Developments

BY
Dr J K PATEL
Director, International Metallurgy Ltd, Oxford, UK
Consultant, CBMM Technology Suisse S.A., Geneva, Switzerland

SYNOPSIS

2019 will mark a historic change in the construction steel rebar market in China with respect to the manufacturing process route and steel chemical composition alloy design. This change has been brought about from the implementation of a new version of GB/T 1499.2018 (Steel for the reinforcement of concrete - part 2: Hot rolled ribbed bars).

The paper provides the latest overview of the Chinese steel rebar market in terms of output, grades produce and an overview of GB/T 1499.2018 Part 2. It presents the latest product developments that have been undertaken to comply with the new standard, from which key components are also presented and discussed. Attention is given to a newly applied metallurgical alloy design strategy and process route in this highly cost sensitive and fundamental steel construction product, detailing a practical approach supported with recent findings.

The paper concludes with a perspective on the wider implications for the ASEAN and neighbouring regions from the introduction of this new standard.

Keywords: Rebar, Cost Effective, Standards, Microstructure, Niobium.

1. **Chinese steel rebar market**

The most recent short-range outlook for global steel demand in 2018 published by the World Steel Association predicts a demand of 1,658Mt in 2018, an increase of 3.9%, and 1,681Mt in 2019 [1]. Out of this China is expected to have a demand of 736.8Mt finished steel products in 2018, or 44% of the world total. In comparison, global crude steel production totalled 1,673Mt in 2017 of which China accounted for 831,728Mt or 49.7% i.e. half of global output, and projections for 2018 is that China will finally surpass 50% in 2018. It is estimated that 200Mt (i.e. 23-24%) of China’s output will be destined towards the production of steel reinforcement bar (i.e. rebar). With an estimated global demand of 391Mt [2] this represents 51.5% of global requirement, almost equal to that of crude and finished steel outputs.

Figure 1 highlights how rebar production in China has grown from 58Mt in 2004 to 200Mt in 2017, peaking at 25.7% in 2014 where demand reached 212Mt. Current forecasts estimate that although growth in the construction sector did not slowdown in recent years, rebar demand in China will remain between 190-210Mt over the next few years and then gradually fall over time as the economy further develops towards maturity. Nevertheless, due the sheer
size of the Chinese market any developments in demand, production and related standards can have a meaningful stimulus in other regional markets.

Correspondingly, as the Chinese rebar market has grown over time together with infrastructure and building requirements, the type of rebar used has also evolved. It was in early 2012 that The Ministry of Industry and Information Technology (MIIT) and the Ministry of Housing and Urban-Rural Development jointly issued guidelines promoting the use of higher strength steel products. The original and ambitious plan was to eliminate the use of 235MPa and 335MPa strength rebar by May 2013 and to gradually raise the ratio of higher strength 500MPa rebar, with an ultimate goal to make higher strength rebar accounting for 80% of output and 65% of consumption in domestic buildings by the end of 2015. However, due to the widespread use of 335MPa rebar in the market and that significant investment would be required by the vast majority of small and medium sized mills, the phasing out of 335MPa rebar was delayed by a further 5 years, to 2018.

Figure 1: Rebar output in China 2004-17.

Figure 2 highlights that in 2013, 335MPa rebar accounted for just over 40% of the rebar market hence the acceptable reason for the delayed phase out. By 2017, the market share had reduced to <5%, with the majority of grade being 400MPa, or HRB400. Therefore, making it an appropriate time to introduce a revision of the national standard for steel ribbed reinforcement bars for concrete, GB1499.2.

Figure 2: Rebar grade strength China 2004-17.
2. **Chinese Standard GB1499.2**

The Chinese national standard, GB1499 part 2, specifically refers to steel ribbed reinforcement bars for concrete, and corresponds to the international standard ISO 66935-2:1991. The standard was last revised in 2007, which was a revision of the 1998 version. One of the main changes in 2007 was the addition of hot rolled bar with ultra-fine grains (designated HRBF) at three strength levels HRBF335, HRBF400 and HRBF500. This is defined as being formed by control rolling and control cooling in the hot rolling process. With the metallurgical structure mainly consisting of ferrite and pearlite, and the grain size being less than level 9 in accordance to GB/T6394 (which equates to 14.1µm linear intercept or 15.9µm average diameter). Whereas the standard hot rolled bars (i.e. HRB) is said to be delivered in the hot rolled condition, with its metallurgical structure mainly consisting of ferrite and pearlite; no other items that can impact the performance of steel bar are allowed [3]. This version of the standard was introduced in 2007, when the rebar market in China was approximately 100Mt and 67% of the grades produced were either ≤335MPa yield strength. Since then the market has doubled in size to 200Mt and is currently worth US$115-120bn in revenue.

Furthermore, tragically in 2008 China experienced one of the largest loss of life in recent history with the 8.0 magnitude Sichuan earthquake, killing an estimated 69,000 people and 18,000 people being listed as missing. It is reported that 5.4 million buildings collapsed and a further 21 million buildings were damaged. The direct economic loss was estimated at US$126bn [4]. Post event investigations found that a notable contributory factor to the large-scale loss of life was poorly designed and constructed reinforced concrete buildings using substandard materials. Subsequently, new design codes were issues in late 2010 which took effect in August 2011 with the aim to restrict and gradually eliminate the use of lower strength bars (i.e. <335MPa).

![Acceptable](image1.png) ![Not allowed](image2.png) ![Possible but likely not accepted in practice](image3.png)

**Figure 3**: Typical macroscopic characteristics of rebar under GB1499.2-2018

![Figure 4: Rebar Vickers hardness measuring point position under GB1499.2-2018](image4.png)

The path to eliminate the use of lower strength and poor-quality rebar has been challenging in such a large market. In recent years the spot-light has fallen on eliminating steel bars produced via the induction furnace route due to poor quality of the recycled steel used, the induction steel making process itself, poor process control and mislabelling. Over the last few years inspection authorities across China have stepped-up actions to eliminate such practises, which has been largely viewed as successful. However, their findings also revealed that some rebar producers were applying higher carbon levels and excessive water cooling to keep overall alloying costs down. Furthermore, cooling practices were not being controlled and so the final tempered martensitic ring formed was eccentric / partially formed or over
developed. The consequences of this resulted in overall poor mechanical properties and premature failure, in particular when the bars were bent or experienced seismic loading conditions. The challenge was how to control and maintain the production and supply of quality high strength rebar across China.

In early February 2018 the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization Administration of the People's Republic of China issued the latest revision of the national standard for steel ribbed reinforcement bars for concrete; GB1499.2-2018. To be implemented in November 2018. This newly revised standard makes significant changes to the manufacture and supply of steel ribbed reinforcement bars for concrete in China, directly addressing the earlier findings of poor-quality rebar material.

Significantly, this new revision will also have a wider and potentially far reaching impact on the supply and demand of ferro-alloying elements based on an estimated rebar volume market of 200Mt. The key changes to the existing standard are as follows:

1. The elimination of a tempered martensitic structure; i.e. effectively no use of conventional QST (Quench and Self-Tempering) practices.
2. The use of microstructural characterisation as a quality control test; i.e. full cross-section microstructure etching using an etching medium (e.g. 2-5% Nital solution) to detect the presence and severity of any tempered martensite structure formed by cooling at the outer edge (see Figure 3).
3. The use of a Vickers Hardness (HV) test as a quality control tests; i.e. the difference in hardness at the very edge (HV) and at the centre of the rebar (HV0) should not exceed 40HV when tested at a loading of 5kg applied for 15 seconds (see Figure 4).
4. The inclusion of a new HRB600 (minimum 600MPa YS) grade.

As with the previous standard, the option remains that additional alloying elements such as niobium (Nb), vanadium (V) and titanium (Ti) can also be applied. There continues to be a restriction on the nitrogen (N) content at 150ppm maximum but can be higher if there are sufficient additional binding elements.

3. Complying with GB1499.2-2018
From November 2018 all rebar produced for the Chinese domestic market will need to be made according to GB1499.2-2018. Leading up to this implementation date and due to the changes outlined in the previous section, Chinese rebar makers are currently revisiting their steel alloy design and process strategies.

3.1 Solution with niobium micro-alloying (an updated approach)
The conventional and longstanding association with niobium micro-alloying is with thermo-mechanical (TM) rolling, whereby a stage will be reached, either before or during finish rolling, when the retardation of austenite recrystallisation is sufficient enough that effectively no recrystallisation of austenite will occur i.e., the non-recrystallisation temperature or $T_{\text{nr}}$ for short. From here, further hot rolling will effectively “pancake”, i.e. elongate, the austenite grains. This critical temperature can be roughly estimated by using published developed equations such as [5]:

\[
(T^\circ) = 887 + 464C + (6445\text{Nb} - 644\text{Nb}^{1/6}) + (732V - 230V^{1/6}) + 890\text{Ti} + 363\text{Al} - 357\text{Si}
\]
It is widely recognized that retardation of austenite recrystallisation is due to the phenomenon of solute drag of niobium atoms and mainly via strain induced precipitation of “fresh” or “new” Nb(C,N) precipitates. The resultant being, with subsequent reductions, that austenite grains become elongated and thereby develop a greater effective grain boundary surface area. Together with the formation of deformation bands within the grains, the ability to nucleate ferrite grains is substantially increased. It is this process of developing a pancaked or elongated, austenite that is referred to as “conditioning” the structure and forms the characteristic part of classical thermo-mechanical rolling (TM) which in turn leads to developing a finer ferrite grain and hence higher strengths and improved toughness (i.e. the Hall-Petch relationship).

According to conventional practises, for this to happen there has to be sufficient solute niobium available at the start of the process as ultimately the quantity of solute niobium will determine the contribution towards TM rolling from solute drag and strain induced precipitation. Therefore, to maximise the contribution of niobium a sufficiently high billet reheating temperature is required to re-introduce into solution the niobium in the high temperature austenite microstructure. This critical temperature is primarily dependent on the carbon (C), nitrogen (N) and niobium content in the steel itself. The equilibrium conditions for the dissolution of the micro-alloy can be calculated through a “solubility product” which effectively provides a guideline for this critical temperature where full solubility is reached. A commonly applied solubility product in the published literature is that presented by Irvine and Pickering [6]:

\[
\log [\text{Nb}] \ [\text{C}+12/14 \text{N}] = 2.26 - 6770 / T
\]

where T is the temperature in Kelvin and Nb, C and N are in wt.%.

The equation indicates that by lowering the carbon and nitrogen levels more niobium can be utilised for the process of TM rolling and also secondary precipitation hardening. Furthermore, for a given a carbon and nitrogen content, applying a higher temperature will permit the use of more niobium (i.e. as a solute). However, for commercial hot rolling of rebar there are some key factors which on initial consideration, based on the above, would suggest that the role of niobium in rebar could be limited: (1) reheating temperatures of \( <1,150^\circ\text{C} \); (2) Higher levels of carbon content of \( >0.20\%\text{C} \), and; (3) High finish rolling temperatures typically \( >975^\circ\text{C} \).

As discussed, the reheating temperature and carbon content are linked via the solubility product. For example, taking a typical rebar composition of 0.25%C and 0.0080%N would require a dissolution temperature of 1,210°C for 0.020%Nb to enter into solution. However, as most rebar producers operate at a reheating furnace temperature of 1,150°C this would only allow 0.0125%Nb to be available as a solute. Furthermore, based on classical TM rolling practices the non-recrystallisation temperature (\( T_{\text{nr}} \)) is calculated at 835°C for 0.0125%Nb, which is obviously significantly lower than a typical finish rolling temperature of 975°C. Infact, 0.05%Nb in solution (at 0.025%C) would be required to have a \( T_{\text{nr}} \) of approximately 1,000°C and in turn this would require a furnace reheating temperature of \( >1,250^\circ\text{C} \).

However, recent studies on a 0.20%C steel found that at temperatures greater than 950°C and with even lower niobium content (where a lower \( T_{\text{nr}} \) would be expected) there is a definitive retardation in recrystallisation of austenite [7-10]. To illustrate this, Figure 3(a) shows the microstructure of a homogenized plate specimen for a 0.20%C-1.0%Mn-0.20%Si-0.017%Nb steel, reheated at 1,250°C for 2 hours. (Note that for this composition the equilibrium
Solubility product temperature is only 1,165°C and the calculated $T_{nr}$ is 935°C.) The mean austenite grain size was 230±5μm in the RD-ND direction. Figures 3 (b) through (d) shows microstructures of samples subjected to a true strain of 0.40 with inter-pass time of 5s at deformation temperatures of 1,050°C, 950°C, and 850°C, respectively via plane strain compression (PSC) test specimens. The specimens were quenched to room temperature immediately after the deformation.

The micrograph shown in Figure 5 (b) exhibit a completely recrystallised microstructure consisting of small equiaxed grains distributed uniformly throughout the matrix. Figure 5 (c) exhibits deformed austenite microstructure but shows also beginning of recrystallisation while that shown in Figure 5 (d) exhibits a highly deformed microstructure with complete unrecrystallised grains. Whilst the results are to be expected at the lower deformation temperatures, those at 1,050 and 950°C are noteworthy and demonstrate that well above the calculated $T_{nr}$ for this steel, the softening of the austenite structure is sufficiently retarded promoting a level of austenite grain refinement. Furthermore, at 950°C this also results in a measurable aspect ratio greater than one thereby indicating a slight pancaking of the austenite grain, which ultimately will lead to a finer ferrite grain.

![Figure 5: Optical micrographs illustrating structure prior to deformation at (a) 1250°C; (b-d) deformed microstructures (b) 1050°C; (c) 950°C, and; (d) 850°C after double-hit test at a true strain of 0.40 and quenched [8]](image)

Figure 6 highlights the interpretation of results from further laboratory deformation studies for the 0.20%C-1.0%Mn-0.20%Si steel with varying levels of niobium from 0.007% (termed dilute) through to 0.017%Nb. The fraction softening curves underline that at 1,000°C, the austenite microstructure softens less indicating an increased potential for refinement. The effect is well established even at very low additions of 0.007%Nb and is enhanced at higher Nb solute content. Remarkably, this is enough to limit the amount of softening in the deformed austenite as shown to 20% with 0.015%Nb at 950°C, significantly aiding a meaningful degree of grain refinement (Note: samples are after double hits at a strain rate of 15s$^{-1}$ and 5 second inter-pass times).

The interpretation of Figure 6 allows an important first conclusion to be drawn: that even a relatively minor addition >0.010%Nb is sufficient under certain rolling conditions to cause an
appreciable inhibition of static recrystallisation of austenite at temperatures above the predicted $T_{nr}$.

It is well understood that recrystallisation is retarded only when the precipitation pinning force becomes greater than recrystallisation driving force. In the present hot deformation study, the use of a well-controlled PSC testing method enables the accurate determination of increase in flow stress and hence the stored energy can be measured effectively to calculate recrystallisation driving force. Ongoing detailed TEM studies has already confirmed that there is some degree of precipitation taking place of Nb(CN) within the austenite structure at the higher temperatures. However, it is random in nature but the volume fraction of precipitates is considerably small and alone cannot account for the retardation in softening kinetics [10]. This leads to a likely conclusion that the primary mechanism causing this retardation is due to a strong solute drag effect of the available (solute) niobium present even at these higher carbon levels and high rolling temperatures.

![Figure 6: The influence of niobium content on the fractioning softening characteristics for a 0.20%C steel after double-hit test at a true strain of 0.40 [10]](image)

These results demonstrate that low finish rolling temperatures are not necessarily required to induce grain refinement via conventional TM practices, and it also highlights the powerful effect of small quantities of solute niobium which then leads to the solubility product and optimal reheating temperature.

As stated earlier, most rebar producers operate at a reheating furnace temperature of 1,150°C (±25°C) and this will only allow 0.0125%Nb solute to be made available from a 0.25%C-0.50%Si-0.008%N base steel composition. Therefore, from these findings it would appear prudent to limit the initial niobium content to this level according to the solubility product. However, recent studies and commercial trials have indicated that an initial higher niobium content, greater than the solubility limit, is beneficial in developing a more homogeneous microstructure and developing higher strengths. This is due to the presence of the remaining un-dissolved niobium precipitates pinning and limiting the austenite grain growth during reheating.

The effect of the main micro-alloying elements on the austenite grain size during reheating is well established and shown in Figure 7 [12]. It can be seen that for a plain CMn steel as the reheating temperature is increased, the austenite grain size also increases (non-linearly). A similar trend is observed with other steels containing vanadium, aluminium and niobium respectively, but the temperature at which the grains begin to coarsen (denoted by the hatched...
area) occurs at increasingly higher temperatures. Prior to reaching this coarsening
temperature austenite grain growth is suppressed due to the pinning effect exerted by
the existence of micro-alloyed precipitates that are present from the originally cooled as-cast
billet and/or formed during the reheating stage itself (for reference, for aluminium only
containing steels the precipitate is that of aluminium-nitride, AlN).

As to be expected due to the lower solubility product of vanadium it is the first precipitate to
enter into solution at around 1,000°C (i.e. effectively dissolve in atomic form into the matrix)
and in doing so, the austenite grain boundary is no longer pinned and consequently coarsens.
Above this temperature, for the vanadium micro-alloyed steel, the austenite grains coarsen
rapidly and the grains are seen to grow even larger than a plain CMn steel (see Figure 7). In
contrast, the niobium micro-alloyed steel grain size remains small and stable up to 1,155°C
indicating that there is a much higher pinning force suppressing grain coarsening, compared
to the vanadium micro-alloyed steel. **It is also this behavior of niobium which can be
gainfully used in the production of rebar.**

Furthermore, several studies have also shown that, besides the pinning exerted by niobium
precipitates, the solute drag effect of niobium in solid solution form plays an important role
in the suppression of austenite grain growth in niobium micro-alloyed steels [13-14]. The
niobium solute drag effect on grain growth decreases with increasing temperature because the
grain boundary can gradually break away from the solute atmosphere in the higher velocity
region at higher temperatures. This results in the mean austenite grain size sluggishly
increasing with temperature at the low temperature region, while it significantly increases at
the relatively high temperature region [13], as highlighted in Figure 7. Therefore, both grain
boundary pinning and solute drag must be considered when determining the austenite grain
coarsening kinetics.

To determine the austenite grain coarsening characteristics of commercially produced
niobium micro-alloyed rebar steels, samples were taken from a 16mm diameter air-cooled
rebar (min 400MPa yield strength; HRB400) for subsequent heat treatment studies. Samples
were heat treated to a range of temperatures from 1,050 to 1,300°C and held for 120 minutes
before water quenching. The chemical composition of the steel is provided in Table 1.

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>Cr+Ni+Cu</th>
<th>Nb</th>
<th>V</th>
<th>CEQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB400</td>
<td>0.24</td>
<td>1.25</td>
<td>0.50</td>
<td>0.027</td>
<td>0.030</td>
<td>56ppm</td>
<td>Residual</td>
<td>0.030</td>
<td>---</td>
<td>&lt;0.45</td>
</tr>
</tbody>
</table>

Samples were then suitably etched to reveal the prior austenite grain boundaries and analysed
to determine both the average austenite grain size and importantly, also the distribution.
Figure 8 shows the optical microscopy images of the developed austenite grains at various
temperatures and also the average measured grain size.

The results are clearly in line with other published findings [12] as shown earlier, where
above 1,150°C the reheated austenite grains are seen to coarsen as the niobium precipitates
start to loosen pinning force. Whilst further studies are required to determine the true extent
of the pinning force and solute drag contributions, from a commercial perspective there is
confirmation that maintaining some niobium precipitates during reheating of billets is
advantageous. Furthermore, and importantly, when using higher reheating temperatures not
only does the average austenite grain size increase, but the overall distribution increases; as
shown in Figure 9.
Figure 8: Austenite grain coarsening characteristics for a CMnSiNb micro-alloyed rebar steel.

Whilst the average austenite grain size is often used to determine the succeeding metallurgical behaviour during rolling, the overall distribution also plays an important role in determining the final microstructure. As evidenced in Figure 9, a lower reheating temperature will result in a much narrower distribution and this can only help in producing a more homogeneous final microstructure, and by default, more stable mechanical properties.

Figure 9: Austenite grain size distribution for a CMnSiNb micro-alloyed rebar steel at various reheating temperatures from 1,050 to 1,300°C.

This is demonstrated by examining a commercially produced 0.032%V only micro-alloyed 25mm diameter rebar steel, which was reheated at 1,150 – 1,175°C before hot rolling (see Table 2 for chemical composition). As this steel only contained vanadium, the starting austenite grains would have already coarsened at 1,000°C as shown earlier in Figure 7. Following hot-rolling this rebar was air-cooled and should have developed a predominately ferrite-pearlite microstructure. However, as the starting austenite grains were large and also the expected distribution of grains would have been broad, i.e. the existence of some very large grains at the extreme end of the distribution (see the equivalent 1,250°C distribution in Figure 9 for comparison), the final transformed microstructure consisted of a mixture of allotriomorphic ferrite, primary and secondary Widmanstätten ferrite, bainite and pearlite. This is shown in Figure 9 along with the corresponding stress-strain curve.
Table 2: Chemical composition of a V micro-alloyed HRB400 rebar steel.

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>Cr+Ni+Cu</th>
<th>Nb</th>
<th>V</th>
<th>CEQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB400</td>
<td>0.23</td>
<td>1.38</td>
<td>0.45</td>
<td>0.025</td>
<td>0.030</td>
<td>80ppm</td>
<td>Residual</td>
<td>---</td>
<td>0.032</td>
<td>&lt;0.45</td>
</tr>
</tbody>
</table>

Figure 10: Final (mixed) microstructure and stress-strain curve for a CMnSiV micro-alloyed rebar steel.

Although the strength of the rebar was sufficient, the stress-strain curve exhibited a small yield point elongation (YPE). Some recent publications have reported that the presence of adequate volume fraction of coarse / upper bainite, large acicular or Widmanstätten plate microstructures not only results in lower YPE but also leads to lower yield strengths [15-16]. Whilst the exact mechanism to the formation of Widmanstätten microstructure is still not completely understood, it is widely accepted that the presence of larger austenite grains will increase the hardenability of the steel through the promotion of such bainitic and coarse Widmanstätten / acicular plates. In Figure 10, the prior austenite grain boundary is clearly demarcated by the allotriomorphic ferrite and the large austenite grain size are observed to be at least 90-100µm in diameter in this one example. In comparison to the CMnSiNb rebar (see Figure 9), this corresponds to the upper end of the grain size distribution and also fits as an example of a coarse grain produced at higher temperatures.

These recent findings, together with previously published works, provide a progressive pathway for the use of niobium micro-alloying towards the commercial production of rebar, and specifically towards compliance for the newly revised Chinese rebar standard GB1499.2-2018. The results highlight, contrary to previous convention, that niobium micro-alloying at levels up to 0.030%Nb is still very relevant even with low reheating furnace temperatures (1,150°C (±25°C)) and at higher carbon content (0.20 – 0.30%C). In summary:

- The addition of niobium at levels above the calculated solubility product. For example, for the production of HRB400 a level of 0.025 to 0.030%Nb would be appropriate at a reheating furnace temperature of 1,150°C (±25°C) for a typical carbon content in the region of 0.25%C.

- The presence of some “undissolved” Nb-precipitates is beneficial in controlling and suppressing austenite grain coarsening / growth during billet reheating. This not only limits the average austenite grain size, but also narrows the distribution and limits the volume fraction of coarser grains. Combined, this leads to a more homogeneous final microstructure upon transformation.
• Although helpful, it is not necessary to finish rolling at low temperatures as per conventional / classical TM practise. The presence of solute niobium atoms (even at low levels of 0.007%Nb) and strain induced precipitation significantly retards austenite recrystallisation during early stages of rolling and coupled with dynamic recrystallisation (followed by meta-dynamic recrystallisation) results in finer austenite grain size prior to transformation.

• The presence of solute niobium following hot rolling increases the hardenability of the steel by promoting the formation of bainite [17] in a positive way as long as the austenite grains are relatively fine and within a narrow distribution.

• The additional of niobium at 0.020%Nb has been found to refine the interlamellar spacing of second phase pearlite for a typical rebar steel [18]. This will result in an increase in yield strength and moreover, the tensile strength, as is well established for 0.80%C steels (i.e. rail steels) [19].

• The presence of solute niobium following hot rolling will also provide additional strengthening contribution from fine nanometre sized precipitates of Nb(C,N) during cooling and transformation.

4. Industrial trials and results

In support to rebar makers for the implementation of GB1499.2-2018, a number of successful commercial trials were undertaken in China adopting the recent findings. Some highlights are reported below for the production of grades HRB400 and HRB500.

4.1 HRB400+Nb

An industrial trial for the production of HRB400 with niobium (only) was undertaken at a primary rebar producer. Several heats were successfully made and continuously cast into billets via a multiple strand curved caster. Billets were surface inspected and passed quality control prior to cold charging in the reheat furnace set to target temperature of approximately 1,150°C. On discharge, billets were descaled and hot rolled under standard operating practices to a range of rebar diameters from 12 to 25mm. Finish (i.e. exit last rolling stand) rolling temperatures averaged 1,000°C (±25°C) and bars were given a “very weak” cool to generate a degree of undercooling prior to entry onto the cooling bed, still in the austenite phase, and naturally air-cooled to room temperature. Based on literature findings to limit the formation of Widmastätten ferrite and also to suppress subsequent grain growth following hot rolling, it was possible to apply a “very weak” cool via the existing accelerated cooling device without inducing a tempered martensite ring.

Table 3: Chemical composition of a Nb micro-alloyed HRB400 rebar steel.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Dia.</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>Cr+Ni+Cu</th>
<th>Nb</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB400</td>
<td>12mm</td>
<td>0.23</td>
<td>1.24</td>
<td>0.40</td>
<td>0.020</td>
<td>0.035</td>
<td>60ppm</td>
<td>Residual</td>
<td>0.025</td>
<td>---</td>
</tr>
<tr>
<td>HRB400</td>
<td>18mm</td>
<td>0.20</td>
<td>1.20</td>
<td>0.30</td>
<td>0.030</td>
<td>0.025</td>
<td>60ppm</td>
<td>Residual</td>
<td>0.027</td>
<td>---</td>
</tr>
<tr>
<td>HRB400</td>
<td>25mm</td>
<td>0.23</td>
<td>1.35</td>
<td>0.35</td>
<td>0.025</td>
<td>0.030</td>
<td>60ppm</td>
<td>Residual</td>
<td>0.030</td>
<td>---</td>
</tr>
</tbody>
</table>

The chemical composition of the rolled steels are provided in Table 3 and it is worth noting that the niobium content was increased with the rolled diameter from 0.025wt.% at 12mm to 0.030wt.% at 25mm. In part this was undertaken to compensate for the effective total area
reduction ratio being considerably less at 25mm than 12mm due to the same starting billet dimension. At this chemical composition the calculated solubility product [6] for the 12mm rebar is 1.235°C, however as a standard operational reheat temperature of 1,150°C was used it is estimated that 0.015%Nb was available in the solute form. To test the impact of a higher reheating temperature one set of billets were heated 70°C higher to 1,220°C which would have resulted in approximately 0.023%Nb to be available in the solute form (i.e. nearly all of the addition made). Under traditional TM practices this would result in a higher final strength due to the availability of more solute niobium.

The results of the rolling trials are presented in Figure 11 and show that all properties of yield, tensile, elongation and TS/YS ratios were fully met and compliant with GB1499.2-2018. Furthermore, as can be seen from the developed Agt. (%) and TS/YS>1.25, the developed rebar also satisfied requirements for grade HRB400E (i.e. for seismic applications). Of interest was the results highlighted in the red boxes for the conventional 1,150°C and higher 1,220°C furnace reheating temperatures, where in fact the final yield strengths were not higher for the billets heated at 1,220°C despite having almost double the solute niobium present. Thus, providing further positive evidence to support the practice of applying a reheating temperature below the calculated solubility product to prevent austenite grain coarsening.

Figure 11: Mechanical properties of HRB400+Nb rebar at 12, 18 and 25mm diameter.
From optical metallography studies the final developed microstructure was predominately equiaxed polygonal ferrite and pearlite, as shown in Figure 12. Although there are signs of other microconstituents, the volume fractions are extremely small and did not affect the yielding characteristics. As expected, with a large diameter the final microstructure is coarser due to lower levels of reductions experienced (i.e. reduced effective total area reduction ratio).

![Microstructure Images]

**Figure 12:** Final microstructure at core of HRB400+Nb rebar at 12, 18 and 25mm diameter.

### 4.2 HRB500+Nb+V

For the development of a higher strength HRB500 (minimum yield strength of 500MPa) rebar, the alloy design approach taken was to supplement the existing alloy design of HRB400+Nb grade. The most obvious candidate was to use vanadium micro-alloying additions to provide further precipitation strengthening during the cooling process post hot-rolling. As this grade had already been developed by the rebar producer using vanadium only (with 0.090%V) it was agreed to use a base niobium approach (from the learning of the HRB400 trials) and supplement this by vanadium.

Two industrial trials where undertaken for the production of HRB500 on a similar basis as described before. On discharge, billets were descaled and hot rolled under standard operating practices to a range of rebar diameters from 16 to 25mm. Finish (i.e. exit last rolling stand) rolling temperatures again averaged 1,000°C (±25°C) but for this trial rolled bars were only air cooled on the cooling bed to room temperature.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Dia.</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>Cr+Ni+Cu</th>
<th>Nb</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-only</td>
<td>16-25mm</td>
<td>0.25</td>
<td>1.55</td>
<td>0.50</td>
<td>0.025</td>
<td>0.030</td>
<td>150ppm</td>
<td>Residual</td>
<td>---</td>
<td>0.090</td>
</tr>
<tr>
<td>NbV</td>
<td>16-25mm</td>
<td>0.24</td>
<td>1.55</td>
<td>0.53</td>
<td>0.020</td>
<td>0.030</td>
<td>120ppm</td>
<td>Residual</td>
<td>0.020</td>
<td>0.070</td>
</tr>
<tr>
<td>NbV (lean)</td>
<td>16-25mm</td>
<td>0.25</td>
<td>1.55</td>
<td>0.50</td>
<td>0.025</td>
<td>0.030</td>
<td>80ppm</td>
<td>Residual</td>
<td>0.025</td>
<td>0.045</td>
</tr>
</tbody>
</table>

The chemical composition of the rolled steels are provided in Table 4 and it is worth noting that the applied furnace reheat temperature was between 1,150 and 1,175°C which would
have resulted in approximately 0.016%Nb to be available as a solute. For comparison the original V-only composition is provided together with a Nb+V and a Nb+V with a lower vanadium content (termed “lean”).

The results of the rolling trials are presented in Figure 13 and show that almost all properties of yield, tensile, elongation and TS/YS ratios were fully met and compliant with GB1499.2-2018. Furthermore, as can be seen from the developed Agt.(%) and TS/YS>1.25, the developed rebar also largely satisfied requirements for grade HRB500E (i.e. for seismic applications). Interestingly the trial results showed that lowering the vanadium content by a further 0.025% from 0.070 to 0.045%V caused a drop in YS of 60-100MPa and this was deemed too much as the final strengths were very close to the 500MPa minimum requirement. Therefore, as the additional strengthening over HRB400+Nb was coming from the addition of vanadium, and from the results, it is reasonable to proposed that a composition of CMnSi + 0.025%Nb + 0.055%V would be adequate to meet HRB500 and HRB500E.

![Figure 13: Mechanical properties of HRB500+Nb+V rebar at 16 to 25mm diameter.](image)

From optical metallography studies the final developed microstructure was predominately equiaxed ferrite, pearlite and bainite, as shown in Figure 14. Although there are signs of other microconstituents such as secondary Widmanstätten ferrite, the volume fractions are sufficiently small and did not affect the yielding characteristics. Unlike the HRB400 microstructure, the ferrite grains are mostly located at the prior austenite grain boundaries. Furthermore, despite the 0.045%V addition, the role of niobium in limiting the austenite grain size is seen in Figure 13 with an observable maximum grains size of 60µm. This is in sharp contrast to that shown earlier in Figure 10, for a 0.032%V only rebar where the prior
austenite grain size was observed to be at least 90-100μm in diameter. Although the strength of the rebar was just reaching 500MPa, the stress-strain curve exhibited also exhibited a small yield point elongation (YPE), which is attributed to the nature of the micro-constituents and respective volume fractions.

![Image](image_url)

**Figure 14:** Final microstructure and stress-strain curve for a CMnSiNb+V (lean) micro-alloyed rebar steel.

5. **Cost effective and stable metallurgical path**

By its very definition, the commercialisation of any “commodity” product makes it highly sensitive to overall production costs and final margins. This is especially true to producers of steel rebar. Consequently, all producers will have to hand at least one alternative proven steel chemistry alloy design for a given grade in order to have the flexibility to respond to changes in raw material and ferro-alloy prices. As discussed earlier, historically, it is reasonable to acknowledge that rebar producers have tended to opt for vanadium as the main micro-alloy of choice. The main reasons for this being: (1) vanadium having a higher solubility than niobium; (2) high finish rolling temperatures typically above 950°C so limited TM rolling potential, and; (3) high carbon content of the steel so limiting the amount of solute niobium that can be utilised.

However, results from laboratory investigations presented in this paper and other recent publications, under pinned by commercial rolling trials, have shown that there is an important role for small additions of niobium micro-alloy in the range of 0.020 to 0.030wt.%Nb in existing rebar grades. The results and discussion have presented an updated approach to the use of niobium micro-alloying in rebar, which until now has not been applied since the introduction of Quench and Self-Tempering (QST) route via an accelerated cooling device. Importantly, this now provides another feasible alloying design option for rebar producers to consider.

Furthermore, as demonstrated and well established, niobium is able to provide strengthening contributions from at least three different paths: (1) grain refinement of the final microstructure (i.e. austenite, ferrite and pearlite interlamellar spacing); (2) increased hardenability through the effect of solute niobium, and; (3) precipitation strengthening post rolling during transformation and/or in the final matrix. This is unlike vanadium which largely provides its strengthening contribution through the one path of; (3) precipitation strengthening. Being reliant on only one path to deliver all the additional strengthening contribution holds inherently higher risk. This is further compounded with the knowledge that the level of precipitation strengthening is very much dependent on the cooling rate as the rebar cools post rolling to room temperature. As to be expected a smaller diameter rebar will
naturally cool much quicker than a larger diameter. Consequently, it is reasonable to assume that for a fixed micro-alloy solute content the amount of precipitation strengthening will also vary due to the different cooling characteristics. Therefore, it would prudent to spread the strengthening contributions to different mechanisms and thereby have a more robust and stable pathway.

With the imminent change to the Chinese rebar standard in November 2018 and producers reverting to the use of ferro-alloys for strengthening contributions, there will undoubtedly be upward pressures on both price and availability of some ferro-alloys such as vanadium which have tended to be the micro-alloy of choice (based on previous conventional thinking) for rebar producers. Indeed, in recent months the price of ferro-vanadium has substantially increased from US$60/kg to over US$120/kg in October 2018.

For rebar, the use of niobium is largely limited due to the processing conditions and carbon content. Nevertheless, judicious amounts of 0.020 to 0.030%Nb can still be successfully used as a cost-effective alternative to vanadium (e.g. for grade HRB400) whilst also providing a stable and lower risk pathway to achieve final mechanical properties. Accordingly, rebar producers are encouraged to adopt a CMnSi + base Nb alloy design approach to establish a robust platform on to which other alloying elements can be supplemented to achieve the require mechanical properties (e.g. for grade HRB500).

6. **Wider implications of GB1499.2-2018**

The Asian region is expected to produce between 44-45Mt of rebar in 2018 and over the next three years the annual pace of construction output growth in India is anticipated at 20% and smaller Asian economies are expected to show rates higher than 10% [2]. This all means that despite a levelling off of rebar demand in China, there will still be material growth in the neighbouring regions and opportunities for export.

Like China, all these regions are prone to natural disasters such as earthquakes and resulting tsunamis, as tragically witnessed over the last few decades. Like China used to do, many of the smaller ASEAN countries are still using lower strength rebar grades and various adaptations of QST practices. Indeed, a recent market investigation undertaken in India highlighted examples of sub-standard rebar that is in circulation [20]. With the changes in building design codes, crackdown on poor quality steel producers, and now material specification amendments and quality assurance checks, China will soon be producing high quality rebar covering standard and seismic conditions. Consequently, this will only hasten other regional players to address shortfalls in their rebar quality and design codes etc. hopefully before the occurrence of any major natural disaster to which there will be no excuse in having knowingly used sub-standard materials.

Furthermore, as part of its Belt and Road Initiative China is actively building massive amounts of infrastructure connecting it to countries around the world. A significant portion of these overseas infrastructure projects are also being built by Chinese firms that will also use GB specifications and hence increase the likelihood of local adoption of GB standards.

Beyond the actual rebar standard, and as eluded to earlier, the introduction of GB1499.2-2018 has already started to have an impact on the price and availability of ferro-vanadium. This sudden demand will only increase into 2019 as more rebar producers adjust their alloy designs and alloying practices. To highlight this, assuming only 20% of the Chinese market readily adopts the new standard, if using a vanadium only alloying design for HRB400 (>90% of the market) then this alone would require around 15,000 to 16,000t of ferro-
vanadium with a current market revenue value approaching US$2bn. Unquestionably, such sudden demands will have repercussions elsewhere in other markets reliant on ferro-vanadium and may even initiate a new wave of investment into new rebar processing lines with capabilities to finish roll at lower temperatures to take full advantage of conventional TM rolling practices.

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