Metallurgical Benefits of Vanadium Microalloying in Producing High Strength Seismic Grade Rebar

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Abstract: It is essential to select appropriate materials for reinforcing bars (rebars) in order to assure adequate seismic performance, and there are several international standards defining specifications. The critical properties of seismic resistant rebars have been identified and the pros and cons of the popular manufacturing processes, quenching and self tempering (QST) and microalloying (MA), have been reviewed.It has been shown that vanadium microalloying provides the best combination of properties, fulfilling all of the essential performance criteria, as well as minimising problems during important fabrication operations and offering ease of use benefits for the steelmaker during casting and rolling.

0 Introduction

The need for special designs and materials to enable buildings to withstand earthquakes has been recognised and understood for many years, yet we still occasionally witness the terrifying impact of unpredictable seismic events.

Recent tragedies in China and Haiti have served as timely reminders, and have justifiably received global attention, leading to calls for improvements in building design and construction.

Many of the buildings damaged or destroyed in these catastrophic events were old, and not constructed to the current highest standards, but even today buildings are being erected with inadequate earthquake resistance and every effort should be made to reverse this situation.

The use of reinforced concrete is a rapid and cost effective construction method, and in such structures the inclusion of steel reinforcing bar (rebar) provides essential strength and stability to the concrete, including the capacity to absorb seismic energy during earthquakes. In regions susceptible to seismic activity, such as China, it is important to select appropriate rebar materials specifically designed to provide a higher degree of resistance than normal.

Seismic rebar standards have been developed in many countries, including China, following the design philosophy to allow the steel to deform but not fail during an earthquake. This approach allows the structure to effectively absorb the energy of the earthquake without collapsing.

In order to satisfy this requirement, rebars should possess sufficient strength, adequate ductility and capacity to sustain cycles of deformation with high plastic strains. It is also desirable to be able to predict how a structure will behave under real world conditions and therefore the properties of bars designed for seismic applications should be tightly controlled within specified ranges.

In summary, the essential properties for high performance seismic resistant rebars are listed below[1，2], and the values specified in relevant countries' standards are given in Table 1.

- High yield strength
- Low variation in yield strength
- Good ductility
- High strain low cycle fatigue properties

Table 1 Mechanical property requirements for seismic resistant rebars

Grade	Strength		Ductility		
	Yield Strength, R_e /MPa	Actual Yield strength/R_e /MPa	Actual Tensile/Yield Strength Ratio	Total Elongation A/%	Uniform Elongation A_{gt} /%
Chinese Standard GB 1449.2:2007					
HRB400E HRBF400E	≥400	≤1.3	≥1.25	≥16	≥9
HRB400E HRBF400E	≥500			≥15	
Australian/New Zealand Standard AS/NZS 4671:2001					
300E	≥300	≤1.27	≥1.15, ≤1.5		≥15
500E	≥500	≤1.20	≥1.15, ≤1.40		≥10
British Standard BS 4449:2005					
B500B	≥500	≤1.3	≥1.08		≥5
B500C			≥1.15, <1.35		≥7.5
American Standard ASTM A706/A 706M – 09b					
Grade 60	≥420	≤1.29	≥1.25	≥14 (Φ=10~19mm) ≥12 (Φ=22~36mm) ≥10 (Φ=43~57mm)	
Grade 80	≥550	≤1.23		≥12 (Φ=10-19mm) ≥12 (Φ=22~36mm) ≥10 (Φ=43~57mm	

In addition to the mechanical properties shown above, it is also often necessary to consider fabrication and important characteristics such as bending/straightening and welding.

1 Options for producing high strength reinforcing bars

High strength hot rolled rebars are normally produced by two different processes;

- In-line heat treatment of low alloy C-Mn steels - sometimes referred as Quench and Self Tempered (QST) process
- Microalloying and air cooling – by the addition of V, Nb or Ti

Recently, a new technology, which uses deformation induced ferrite transformation (DIFT) mechanism to produce rebars, with a very fine ferrite grain size, has also been developed but is not yet widely used.

In the QST process, high pressure water sprays quench the bar surface as it exits the rolling mill to produce a bar with a hard, tempered martensitic outer layer, and a soft, more ductile ferrite-pearlite core. This process enables the cost effective production of high strength rebars using low carbon content compositions (Ceq <0.52%)[3] and it is widely used in many countries.

However, there are some disadvantages associated with the QST, that can restrict its application in seismic situations.

From a performance perspective, the composite microstructure, consisting of a hard tempered martennsite outer layer and softer core, results in a lower tensile strength to yield strength ratio compared with microalloyed rebars[3, 4]. As shown in table 1, this is an important characteristic in most seismic rebar standards, and the relatively worse performance of QST rebar limits its use for seismic design applications.

From a fabrication perspective, QST rebars are compromised in terms of welding, bending/rebending and threading performance. Welding can lead to significant softening of the tempered martensite layer, even at relatively low temperatures (>450°C), causing a reduction in strength, and therefore should only be performed if the effects are fully understood and compensated for. The sensitivity of QST rebars to high temperatures is also a critical factor during straightening and re-bending operations of rebars with yield strength of 500MPa or higher, which should be carried out at over 700°C (i.e. well above the softening temperature) in order to minimise work hardening and loss of ductility. QST rebars are also unsuitable for threading because this removes the high strength outer layer and exposes the softer core[5].

In the microalloying (MA) process, small amounts of elements such as Vanadium, Niobium and/or Titanium are added, which promote strength by precipitation strengthening and grain refinement. Despite the additional cost of microalloying, MA rebars possess certain advantages making them an appropriate choice for many high strength applications including seismic.

MA rebars, unlike the QST rebars, have a homogenous cross section in terms of microstructure, strength and ductility. This characteristic allows machining of threads, which is important for mechanical couplers, and can also contribute to better resistance against atmospheric corrosion[6]. MA rebar can be welded without loss of strength and possess higher fire resistance than QST rebars [7].

Vanadium is the most common addition for high strength MA rebar, because it offers the best combination of high strength, good ductility, bendability, easy of welding, mechanical joining and insensitivity to strain aging[8, 9, 10, 11].

The production of vanadium MA rebar is very straightforward and, despite the increased cost of alloying compared with QST, the ease-of-use of vanadium is an important consideration for steel producers.

The high solubility of vanadium carbonitrides in austenite minimises the risk of cracking during continuous casting, and permits the use of economical hot rolling practices compared to the other microalloying choices. Also, vanadium rebars do not require sophisticated cooling lines, and the required microstructures and mechanical properties are achieved directly during air cooling after rolling.

Typically a low reheating temperature of 1100°C is adequate to dissolve all of the vanadium, and this compares favourably with other less soluble microalloying elements. Most of the vanadium is retained in solution during rolling and does not precipitate before ferrite is formed during cooling, therefore allowing the full microalloying potential to be utilised and avoiding property variation due to premature precipitation which can occur with less soluble microalloying elements.

Figures 1 and 2 show the calculated equilibrium precipitation of V(C,N) and Nb(C,N) respectively, in a series of typical V and Nb microalloyed reinforcing steels.

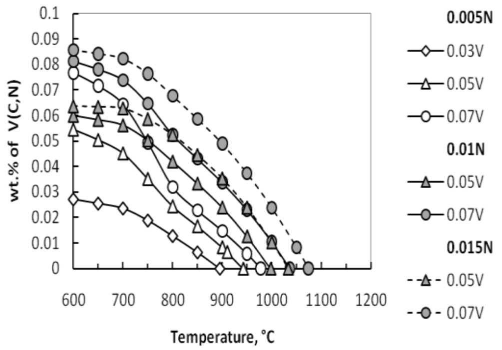


Fig. 1 Precipitation of V(C,N) in vanadium microalloyed reinforcing steels at equilibrium condition (Tukdogan and Rose [12, 13] using FACTSAGE).

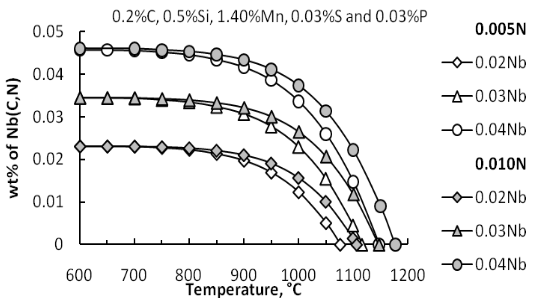


Fig. 2 Precipitation of Nb(C,N) in niobium microalloyed reinforcing steels at equilibrium condition (Tukdogan and Rose [14, 15] using FACTSAGE).

Vanadium carbonitrides tend not to precipitate in austenite and the rolling loads for vanadium reinforcing steels are found to be lower than those for niobium reinforcing steels and similar to those for C-Mn steels when measured in the same temperature range. Therefore, vanadium rebars can be easily hot rolled in the mills designed for C-Mn rebars.

During hot rolling of rebars, high finishing rolling temperatures are inevitable and the conditions of low temperature controlled rolling, which is normally used for niobium steels, are impossible to meet. In addition, low temperature controlled rolling increases the process time and consequently reduces productivity. High finish rolling temperature can be used in vanadium containing steels, since grain refinement is obtained by repeated recrystallization.

Unlike niobium rebars, which must be rapidly cooled after hot rolling to control the subsequent concentration of solute Nb in solution to form fine Nb precipitates in ferrite, Vanadium rebars can be air cooled after hot rolling to achieve required properties. In addition, niobium present in solution in relatively coarse grained austenite may contribute to bainitic transformation during cooling which results in poor bendability and lower toughness[16].

2 Performance considerations of vanadium microalloyed seismic rebar

2.1 Yield Strength

Yield strength is the property that determines the maximum usable strength of a reinforced concrete member. Rebar in the concrete structure should have adequate strength to carry the design loads safely. If the yield strength is high, the rebar will remain in the elastic range during an earthquake. In addition, fatigue strength of reinforcement depends on its yield strength and rebars having higher fatigue strength have better capability of withstanding dynamic loads[17]. The minimum value of yield strength is generally given for a specified steel grade in most of the rebar specifications.

Vanadium increases the yield strength through precipitation of vanadium carbonitrides in the ferrite and by grain refinement [9, 18]. Minimum yield strengths of 400 or 500MPa are routinely achievable, and even up to 700MPa vanadium MA rebars have been successfully produced.

The high solubility of vanadium in austenite has already been mentioned, and the precipitation of fine vanadium carbonitrides in ferrite during/after transformation is the main contributory factor towards high yield strength. The addition of nitrogen increases further the precipitation strengthening since it increases the driving force for nucleation of vanadium nitride (VN) during cooling, resulting in more nucleation sites and a much finer dispersion of VN precipitates.

The beneficial effect of increasing nitrogen on strength, for a given vanadium content, has been shown in research and industrial production [9, 19, 20, 21]. Figure 3 shows the effect of vanadium and nitrogen levels on the yield strength and, as expected, the yield strength increases with the increase in vanadium content. However, this relationship is shifted upwards when the nitrogen content is increased from 40-80 ppm to 80-150 ppm. Therefore, to achieve the targeted yield strength, less vanadium is needed in high nitrogen containing steels. It is also found that the precipitation strength increases with increasing cooling rate and the increase is greater at higher finish rolling temperatures [22, 23]. It has been suggested that increasing cooling rate after rolling suppresses precipitation of V(C,N) in austenite, decreases the γ to α transformation temperature and increases the density of V(C,N) in ferrite. In addition, the precipitates tend to be coarser and less effective in larger diameter bars. The strengthening effect from a given vanadium addition therefore, is slightly less as bar diameter increases[9].

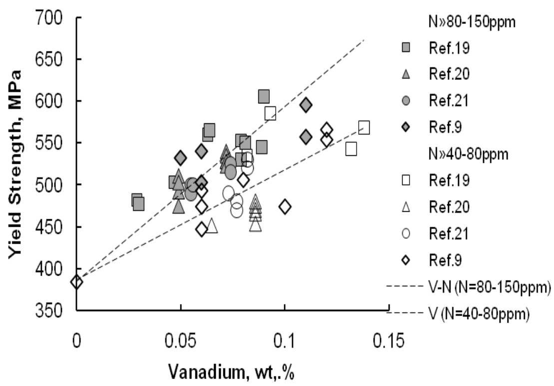


Fig. 3 Effect of vanadium and nitrogen on the yield strength.

Vanadium offers no effective resistance to austenite recrystallization during hot rolling because its high solubility engenders no impeding precipitates. Austenite grain refinement in vanadium steel is achieved by repeated recrystallization after each rolling reduction during hot rolling. In addition, therecrystallized austenite size appears to be fairly constant over a wide range of finish rolling temperatures[24]. Furthermore, the ferrite grains can be further refined by accelerated cooling and by enhanced nitrogen content [25].

2.2 Low Variation in Yield Strength

In order to avoid situations in which reinforced concrete sections become overloaded and risk brittle shear failure during seismic loading, it is considered important to restrict the maximum yield strength of rebars to match the specified level considered in the design. This approach to safe aseismic design criteria, intended to promote ductile failure, is taken into account in modern seismic rebar standards such as GB 1499.2-2007, BS4449:2005, ASTM A706/706M and AS/NZS 4671, which specify both minimum and maximum yield strengths

Vanadium microalloyed rebars exhibit the lowest sensitivity to processing parameters, compared to other microalloyed rebars, and have low variation in yield strength. Figure 4 shows the histograms of statistical analysis of results of actual yield strength to specified minimum yield strength ratio of Grade HRB400 vanadium containing rebars produced by Jinan Steel[26] and Handan Steel [27]. The histograms show normal distributions. The peak values from both producers are around 1.18-1.19 and the maximum value is 1.3, which satisfies the requirement for anti-seismic rebars in the Chinese specification of GB 1499.2-2007.

2.3 Good Ductility

Ductility is an important aspect in the design of earthquake resistant structures. Ductility refers to a structure's ability to undergo large deformation while dissipating energy, without breaking in a brittle and abrupt manner during large earthquakes. Concrete is a comparatively brittle material, and therefore, the reinforcing steel's ductile property is the main contributor to the overall ductility behaviour of reinforced concrete structures. The ductility requirements are defined in terms of two parameters: the tensile strength to yield strength ratio (TS/YS) and the uniform elongation (A_{gt}).

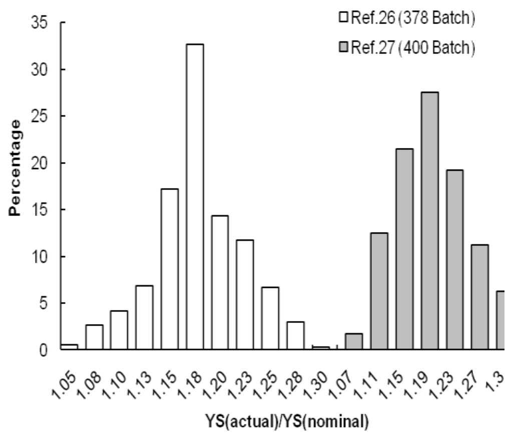


Fig. 4 Histograms of statistical analysis comparing actual yield strength to nominal yield strength ratio

The Tensile Strength/Yield Strength Ratio (TS/YS) ratio is a specific requirement for seismic design, and is required to ensure that inelastic performance of a structure is in a predictable manner. The TS/YS ratio is a measure of the rebars' ability to work harden (i.e. strengthen) when undergoing plastic deformation, and a large value means a greater energy absorption capability before failure. This parameter is to ensure that yielding will not be confined to where it first commences, thereby permitting greater elongation of the rebar before fracture and hence greater ductility of the structural member. If the R_m/R_e ratio is too low, the region of yielding in a rebar does not propagate along the length of the rebar, but rather concentrates in one location. This results in a small number of large cracks developing. Therefore, rebars, which have too low TS/YS ratio, will be less capable of resisting large levels of imposed strain before fracture.

The minimum TS/YS ratio is specified in the specifications for anti-seismic rebars, for example, it is 1.25 in GB 1499.2-2007 and ASTM A706/A706M, 1.08 or 1.15 in BS 4449:2005 and 1.15 in AS/NZS 4671:2001. A maximum ratio is also set in some of the standards, which is 1.35 in BS 4449:2005 for Grade B500C and 1.5 or 1.4 in AS/NZS 4671:2001 for Grades 300E and 500E respectively to ensure that when the steel commences to strain harden the stress in the rebar does not lead to a significant over strength of the structural member.

Additions of vanadium and nitrogen in reinforcing steels increase the yield strength, which results a slightly decrease in the TS/YS ratio, figure 5 [19, 20, 21]. However, vanadium MA rebars have TS/YS ratio values higher or at least equal to 1.25, and normally less than 1.40.

Uniform elongation is also a measure of ability to deform prior to fracture. In general terms, there is an inverse relationship between strength and ductility. However, vanadium strengthened rebars maintain adequate ductility to meet all specifications. The effect of vanadium on elongation is indicated in figure 6[27, 28, 29, 30].

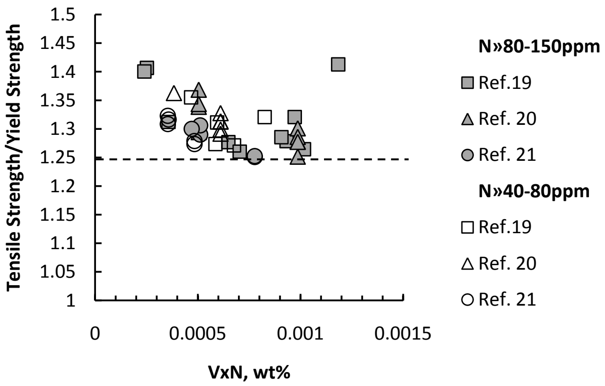


Fig. 5 Effect of vanadium and nitrogen on the ratio of tensile to yield strength

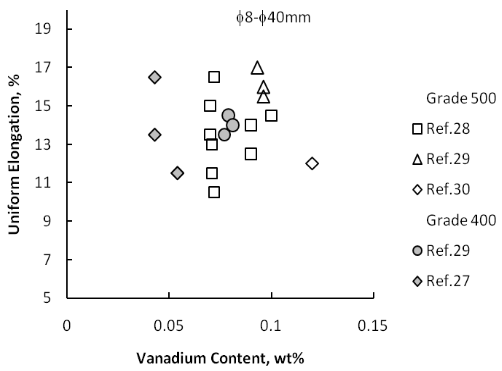


Fig. 6 Effect of vanadium on uniform elongation.

2.4 High Strain Low Cycle Fatigue Properties

In a seismic event, rebers in building structure may be expected to undergo large tension and compression strain reversals of typically one to five fully reversed equiamplitudes. Fracture of longitudinal reinforcing steel due to low cycle fatigue is one of the prominent failure modes for flexural members, with or without low level axial load. Such behaviour is typical for the beams and columns in building frames where large cycle strain amplitudes up to

0.06 may be expected in medium to high seismic risk zones [31].

In seismic areas rebars must have adequate energy dissipation capacity, which characterizes the resistance to failure. The total energy dissipation capacity is evaluated as the sum of the areas formed within the hysteresis loops from a high strain low cycle fatigue test, and an example of fatigue stress-strain hysteresis loop of a 0.22C-0.078V-0.0034N steel rebar is given in figure 7 [32]. The larger the area is, the higher the plastic strain component and the more energy can be absorbed. It has been reported that vanadium microalloyed rebars have superior high strain low cycle fatigue properties than C-Mn rebars [7, 30, 33, 34, 35]. Qin, et.al. [32] showed that the total energy dissipation capacity was 36.7 Jcm^{-3} for a grade HRB400, 0.22%C-0.078%V-0.0034%N reinforcing steel compared with 25.2 J/m^3 for a similar C-Mn Steel. They suggested that the better seismic resistant properties in the vanadium containing steel were due to non-strain aging and lower ductile to brittle transition temperature compared to the C-Mn steel. Strain aging was observed in the C-Mn steel, which influenced strength, ductility and the behaviour of hardening and softening in the cyclical process, resulting in a reduction of energy density.

3 Fabrication considerations of vanadium microalloyed seismic rebar

3.1 Bending/straightening (strain aging behaviour)

Rebar is present in the plastically deformed condition in many regions of the structure, i.e. at design bends, returns, stirrups and so forth, and strain aging can occur in these regions at ambient temperature during and after construction. This results in an increase in the strength, a reduction in ductility and an increase in the ductile to brittle transition temperature, thereby increasing the potential for brittle fractures to occur during an earthquake. For the survival of these reinforced concrete structures during a major earthquake, it is essential that strain aging in rebars should be avoided [36, 37].

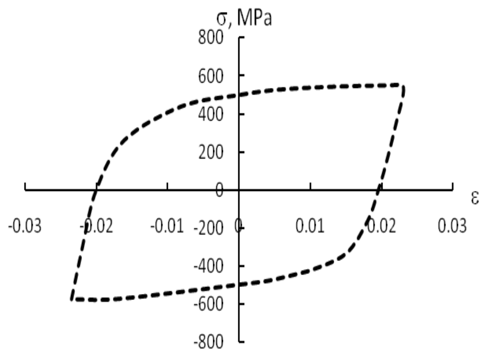
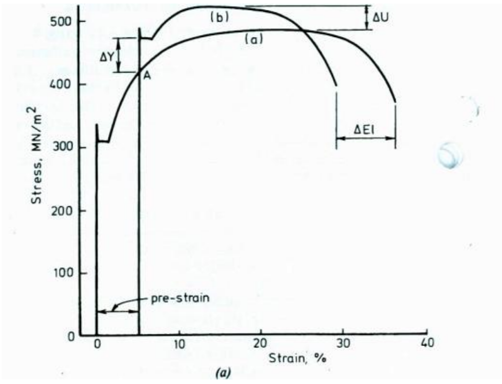


Fig.7 High strain low cycle fatigue stress-strain hysteresis loop of a vanadium microalloyed rebar [32]

Natural aging at ambient temperature in as-hot rolled C-Mn reinforcing steels has been shown to be caused by nitrogen only[36]. Hence, the addition of strong nitride forming elements to reinforcing steels should reduce their susceptibility to natural strain aging. It is well established that a small addition of vanadium to low carbon steels will render these steels non-strain aging by forming stable VN precipitates, thus lowering and in most instances completely eliminating active nitrogen in these steels [32, 36, 38, 39, 40, 41]. However, the phenomenon of aging is not eliminated in niobium steels [42, 43] It is suggested[10] that a V/N ratio of equal or more than 4:1 is necessary to combine with the available nitrogen as VN. An example showing the effect of vanadium on the change of tensile properties (ΔY, ΔY and ΔEl) of a C-Mn steel (0.21C-0.44Mn-0.0058N) and a V (0.21C-0.44Mn-0.060V-0.0056N) steel aged at 100°C for 3 h is given in figure 8 [36]. It can be seen that the addition of 0.06V to the low carbon steel has almost completely eliminated the strain aging.



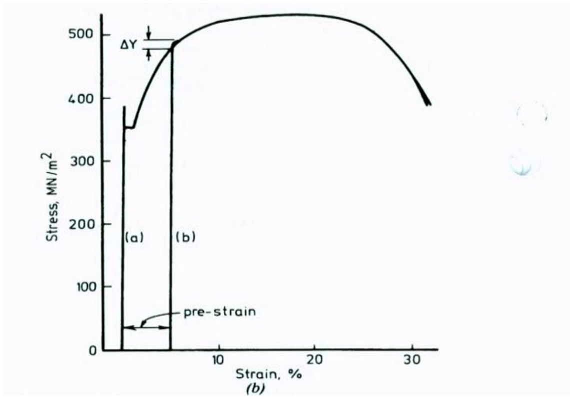


Fig. 8. Stress-strain curves before and after prestraining by 5% and aging at 100°C. ΔY-change in yield strength due to strain aging; ΔU-change in tensile strength due to strain aging; ΔEl-change in elongation due to strain aging. (a) C-Mn steel; (C) V-steel.

3.2 Welding

Rebars should not be welded without regard to steel weldability and proper welding procedures. Standards specify requirements for material intended for welding in terms of carbon equivalent value (CE) and chemical composition restrictions.

CE value is a composite analytical parameter that defines a hardenability of the steel, which is the ability of the steel to form hard, brittle microstructural phases after a particular heating and cooling cycle. Most of the CE formulas show vanadium to have some small adverse effect on the CE values. However, more recent studies [44, 45] have shown that it is not necessary to include vanadium in the compositional characterising paramenter for steels with up to 0.18%V. In addition,the limitation of the maximum CE value is a necessary but insufficient requirement for weldability of rebars, because weldability of rebars is defined by ductility of their welded splices and their strength, which may be reduced after welding.

Vanadium MA steels are readily weldable and the welding techniques are not necessary to be tightly controlled [46]. Vanadium microalloying can bring beneficial effect to weld joint toughness, by virtue of its influence on microstructural development. Vanadium has been observed to result in an increase in the amount of acicular ferrite present in the microstructure of both HAZ and weld metaland this can have a significant beneficial effect on weldment properties [45, 47]. Early work by Sage [9] reported that the resistance to cold cracking during welding of vanadium MA rebar is similar to that of C-Mn steels welded under similar conditions. Recent research [and industrial production [48，49，50] have show that vanadium MA rebar can be successfully welded by various methods, an example is given in Table 2.

4 Conclusions

It is essential to select appropriate materials for rebars in order assure adequate seismic performance, and there are several international standards defining specifications.

The critical properties of seismic rebars are high (and consistent) yield strength and good ductility (as defined by uniform elongation and tensile strength/yield strength ratio). Low cycle high strain fatigue performance is also an important characteristic. Furthermore, it is important to consider aspects of fabrication including welding and bending/straightening behaviour.

Table 2. Mechanical Properties of welding joints of the HRB400 rebars

Welding Method	Rebar Diameter (mm)	Base Steel		Welding Joint				
		Yield Strength (MPa)	Tensile Strength (MPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fracture Position	Bending Test (90°C)	
							d=5a	d=6a
Flash butt Welding (Ref.50)	ϕ16	490/500	665/670		660/675/660	Base Steel 30/106/75mm from the weld	No Cracking	
Flash butt Welding (Ref.51)	ϕ25	470/465/465	655/655/650	510/505/490	655/655/650	Base steel	ok	
	ϕ32	465/465/460	645/640/635	480/500/480	645/625/630	Base Steel		ok

There are different options for the producing seismic resistant rebars, the most popular being quenching and self-tempering (QST) and microalloying (MA), and they have different performance and fabrication characteristics.

QST is the lowest cost process, but the properties are inferior in several ways compared with microalloying. Of the microalloyed options, Vanadium provides the best combinations of properties and also provides ease of use benefits for the steelmaker during casting and rolling.

Vanadium microalloying is considered the optimum approach, and is widely used for the production of high strength seismic rebars, because it fulfils all of the essential performance criteria, as well as minimising problems during important fabrication operations.

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