2013

Towards improved steel alloy designs for control of weld heat affected zone properties

F J. Barbaro
University of Wollongong, fbarbaro@uow.edu.au

Z Zhu
University of Wollongong, zz056@uowmail.edu.au

L Kuzmikova
University of Wollongong, lenka@uow.edu.au

H Li
University of Wollongong, huijun@uow.edu.au

J M. Gray
Microalloyed Steel Institute

Publication Details

Towards improved steel alloy designs for control of weld heat affected zone properties

Abstract

This paper reviews the current technology related to control of weld HAZ properties in high strength steels. The debate related to appropriate balance of Ti and N is addressed and it appears that a stoichiometric ratio provides optimum fracture toughness. The results are significant because despite the well established difficulties in controlling Ti/N ratio, this data now provides guidance in terms of alloy design to achieve optimum fracture toughness in the HAZ of welds. The enhanced resistance to grain coarsening behaviour of high Nb steels has now provided another incremental improvement in the weldability of steels for critical applications such as high pressure gas transmission pipelines. The role of Mo in the alloy design of these new steels is a further activity to be undertaken in the design concepts to further improve the performance and safety of modern steel structures.

Keywords

steel, weld, control, designs, properties, improved, zone, towards, affected, alloy, heat

Disciplines

Engineering | Science and Technology Studies

Steel Alloy Designs for Control of Weld Heat Affected Zone Properties

F. J. Barbaro[1], Z. Zhu[1], L. Kuzmikova[1], H. Li[1], J. M. Gray[2]

1) University of Wollongong, NSW, Australia.
2) Microalloyed Steel Institute, LP, Houston, Texas, USA.

Abstract: This paper reviews the current technology related to control of weld HAZ properties in high strength steels. The debate related to appropriate balance of Ti and N is addressed and it appears that a stoichiometric ratio provides optimum fracture toughness. The results are significant because despite the well established difficulties in controlling Ti/N ratio, this data now provides guidance in terms of alloy design to achieve optimum fracture toughness in the HAZ of welds.

The enhanced resistance to grain coarsening behaviour of high Nb steels has now provided another incremental improvement in the weldability of steels for critical applications such as high pressure gas transmission pipelines. The role of Mo in the alloy design of these new steels is a further activity to be undertaken in the design concepts to further improve the performance and safety of modern steel structures.

Keywords: Titanium, Niobium, precipitation, HAZ, TMCP, weldability.

1 Introduction

Modern high strength steels are manufactured using tailored alloy designs and fabricated using advanced thermomechanically controlled processes. The final mechanical properties of the steel are controlled through development of unique microstructures which are characterised by a fine ferrite grain size and a dispersion of alloy precipitates that optimise strength, ductility and toughness.

The process of welding inherently subjects the steel to elevated temperatures, which significantly modifies these microstructures and therefore the mechanical properties. The region immediately adjacent to the weld, where the temperature approaches the melting point, can be significantly degraded by the extreme grain coarsening that occurs in the austenite phase region. Although many parameters control the microstructure and mechanical properties of HAZ, it is control of the austenite grain size that is critical in terms of the performance of these steels.

Ti microalloying produces a dispersion of stable TiN precipitates which retard austenite grain coarsening by a grain boundary pinning action [1-5], as shown in Figure 1-1. Other methods of HAZ microstructural control have been developed [6] but Ti microalloying, following complete deoxidation, to ensure formation of nitride precipitation, is currently the dominant method employed.
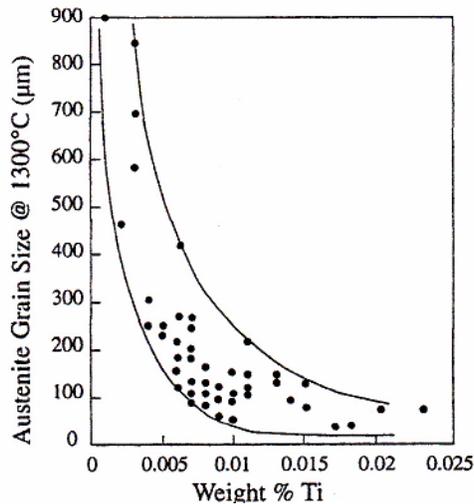
Figure 1-1 The effect of Ti content on austenite grain size at 1300°C [4].

It is true to say that the use of Ti in steels is by far the most complex and least understood of all the microalloying elements. Ti is a strong oxide, sulphide, nitride and carbide former and it is the chemical balance of impurities and processing that determines the final form of the titanium compounds and the resulting properties.

A very fine dispersion of TiN precipates is required to exert a grain boundary pinning action in opposition to the driving force for grain growth. Maximum pinning force (Z) has been shown by Zener [7], to be directly proportional to the volume fraction of precipitation (f) and inversely proportional to the precipitate size or radius (r), as defined in Equation (1). Therefore, a large volume fraction of small precipitate is beneficial for grain size control.

$$Z \propto f/r \tag{1}$$

The approach to achieving the optimum dispersion of precipitates is the basis of ongoing debate among steelmakers and specifiers. Different approaches have been proposed to control the precipitate dispersion but the reported results are generally clouded by the influence of secondary effects associated with base alloy design and processing, including casting condtions.

This paper details the technology of TiN precipitation and recent research that clarifies the current debate regarding appropriate alloy designs of Ti bearing high strength steel grades. The issues associated with the current Ti alloy design is discussed and an alternative incremental approach using increased levels of Nb to improve the weld HAZ properties of these steels is presented.

2 Background

An addition of Ti, following deoxidation and in the presence of N, results in the formation of TiN precipitates which have high thermal stability [8]. As discussed above, the effectiveness of such precipitates is dependent on the size distribution and volume fraction and is related to the solubility product data as shown in Figure 0-1.
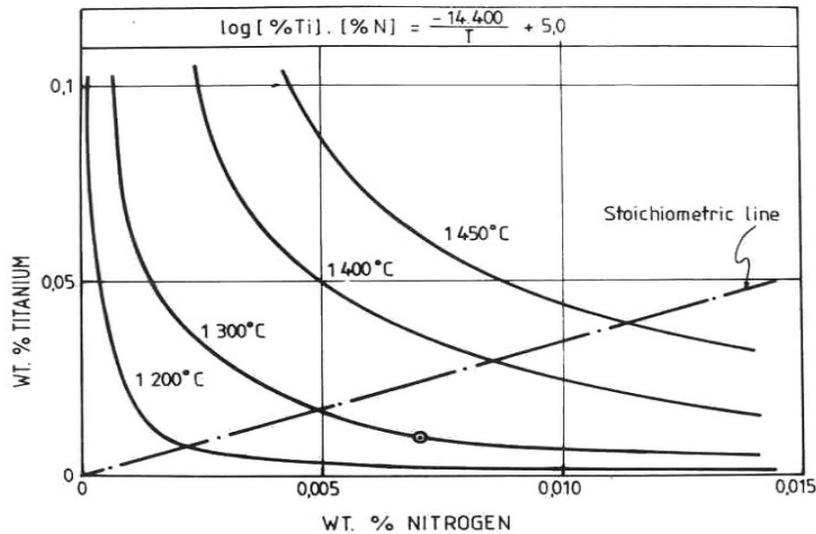
Figure 0-1 Solubility isotherms for TiN in austenite [9].

As the concentration of Ti and N increase, the temperature at which precipitation forms increases and results in the formation and/or growth of large TiN precipitates. Large TiN precipitates which are primarily cubiodal in shape are not only ineffective in grain boundary pinning [7] but also provide sites for the initiation of cleavage fracture [10, 11]. An optimum dispersion of TiN precipitates can be achieved by limiting the overall concentration of both Ti and N, to reduce the temperature of formation and minimise thermally activated duffusion processes that lead to precipitate growth, as shown in Figure 0-1. In other words, a large number of very small precipitates are required to achieve maximum grain size control. The grain coarsening temperature increases when there is a maximum volume fraction of pinning particles.

Therefore a certain volume fraction of precipitation is required to effect grain boundary pinning and a minimum level of Ti is essential to ensure optimum grain size control. Unfortunately, however, current steelmaking practice struggles to accurately control the final level of N and so a specific stoichiometric ratio can be difficult to achieve. A non-stoichiometric ratio, not only results in a non optimal size distribution but also results in either excess Ti or N, which generates the formation of TiC in the former and excess N in the latter. There is also controversy about the role of excess N as some claim that free N is detrimental to toughness [12-15] while others suggest beneficial effects as the N retards precipitate dissolution [16].

It should however be emphasised that the overall performance of the steel is defined by the range of Ti and N levels as well as the casting conditions and the slab cooling rates. The latter processing conditions are also critical, as the as-cast precipitates, especially the detrimentally large precipitates, are difficult to be modified because of their high thermal stability.

In terms of procurement of steel for critical applications such as pipelines, it is appropriate to evaluate steel performance and production capability, with respect to weld HAZ properties. Reliance solely on an alloy design or specification is insufficient when specific mechanical property performance is essential to ensure structural integrity and public safety.

More recently, the work of Zhu et al. [17] has now demonstrated, using detailed quantitative metallography, a more complete understanding of the influence of Ti/N ratio on weld HAZ microstructure. This work utilised a unique set of samples from commercial API 5L grade X70 grade pipe, which were produced through identical procesing conditions and contained the same base chemistry but most importantly with a range of Ti/N ratios for critical evaluation of weld HAZ microstructure and mechanical properties.

As experienced by previous investigators, the inherent difficulty in accurately evaluating a narrow weld HAZ necessitated the use of a Gleeble weld thermal simulator to duplicate sufficient size specimens containing the critical CGHAZ region of the welds. The peak temperature and

cooling rate were directly correlated with the welding conditions employed to ensure identical microstructures and importantly austenite grain size of the real weld.

Metallographic examination revealed the simulated microstructures to primarily consist of an aligned bainitic ferrite with small amount of interlath M-A islands. Hardness values were consistent with the peak hardness recorded in HAZ profiles on the real welds and so confirmed the suitability of the weld simulation conditions.

Although qualitative evaluation of the austentie grain size inidicated minor variations in average grain size, the significant observable difference was revealed using quantitative metallographic techniques. The results presented in Figure 0-2, confirm that a distinct difference in distribution of grain size was observed which suggested that both an increased volume fraction of fine austenite grains and less coarsened austenite grains were present in the steel with a ratio close to the stoichiometric combination of Ti & N. This was further supported by the results of Charpy impact tests, shown in Figure 0-3, which demonstrated a "measurable" improvement in fracture toughness.
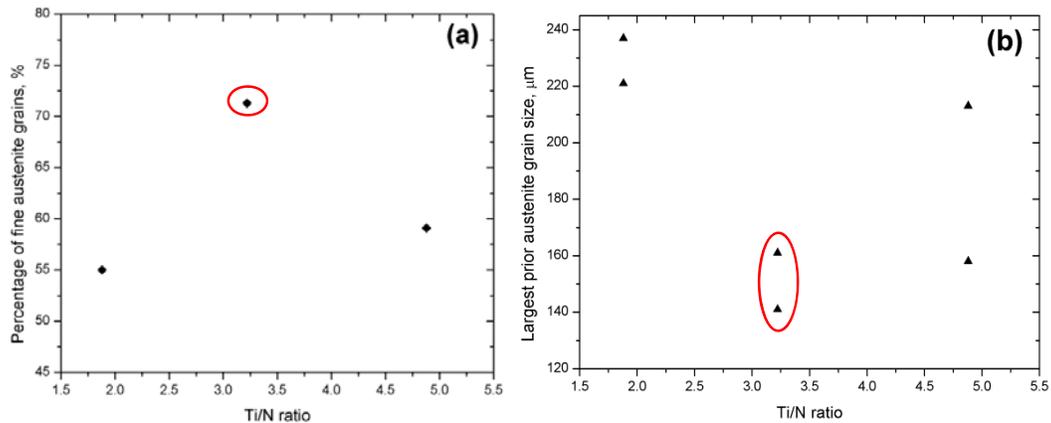

Figure 0-2 Results of statistical analysis of prior austenite grains size in steels with different Ti/N ratios: (a) percentage of fine grains (smaller than 80μm); (b) largest grain size [18].
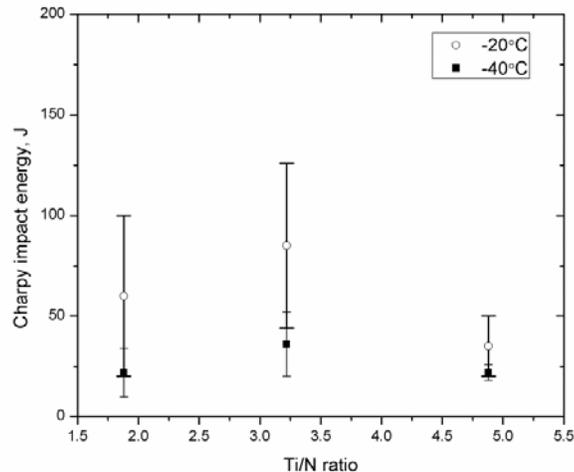

Figure 0-3 Mean Charpy impact energy of the simulated CGHAZ of samples with different Ti/N ratios. Each point is an average of three measurements [18]

Such a fine difference in microstructure and toughness performance would not have been discernible in evaluation of real welds because of the difficulties in evaluating and testing the sharp gradient of microstructures immediately adjacent to the weld fusion line.

It is reasonable to assume that based on these results, the practice of first tier steel producers [19] and thermodynamic considerations, the optimum combination of Ti & N exists around the stoichiometric ratio, at levels that restrict initial formation of TiN below the solidus.

3 High Temperature Processed Steel

A new alloy design, although reported many decades ago [20], has only now been commercially developed and successfully utilised in a number of large international pipeline projects [21, 22]. The steel design typically contains a low carbon content, microalloyed with Ti but with a Nb content in the range 0.08-0.11 wt%, which enables the full capability of Nb microalloying to be effectively utilised in steel manufacture and service performance [23].

It has been clearly demonstrated that Nb provides a number of benefits to the mechanical properties of steels: grain size refinement; lowering the γ to α transition temperature (A$_{r3}$), precipitation hardening and retardation of austenite recrystallisation [24, 25].

It is pertinent to point out the salient features of the high Nb alloy design and the improvements to processing conditions that also provide economic benefits to the steel maker. Key features of this high Nb alloy design includes :

3.1 Reduced carbon content :
  (a) minimizes elemental partitioning, i.e. segregation, during casting, as schematically shown in Figure 3-1 [26]. Avoidance of the peritectic reaction eliminates the involvement of enriched interdendritic liquid during transformation and furthermore provides an extended solidification range in delta ferrite that enhances homogenization of the newly formed solid prior to further transformation on cooling.
  (b) maintains and enhances the solubility of the Nb to assist in the benefits outlined above, Figure 3-2 [26]. Most notably is the delayed precipitation of carbonitrides that enhances the hot ductility and increases the operating window for hot rolling, and therefore reduces mill operating loads. The consequential benefits to available mill uptime and maintenance downs should also be considered.
  (c) reduces carbon equivalent and therefore improves the weldability for reduced susceptibility to hydrogen assisted cold cracking,

3.2 Controlled Ti addition which provides control of nitrogen for selection of optimum NbC precipitation, and avoids the formation of mixed carbonitride precipitates which occur over a larger temperature range.
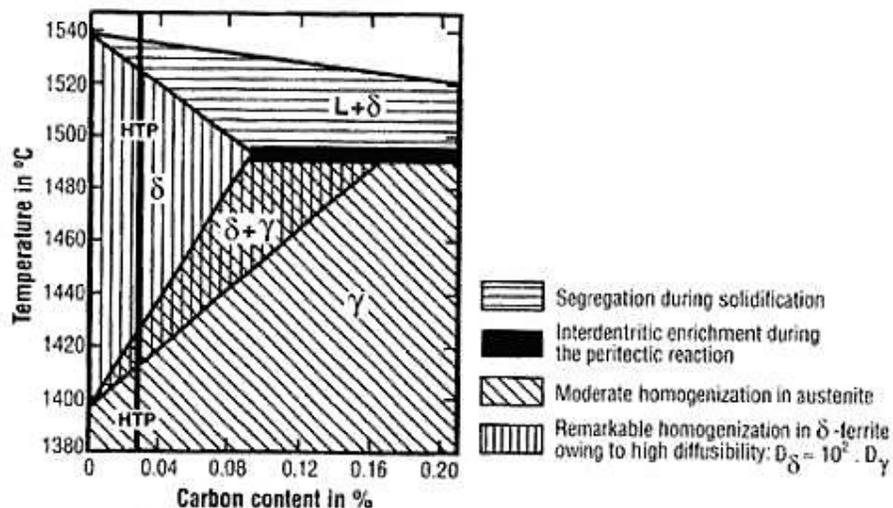

Figure 3-1 Part of the Fe-C diagram with classification of the segregation severity.
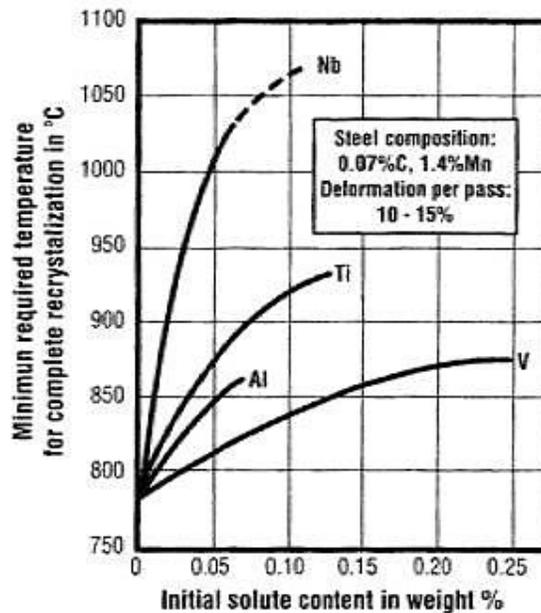
5

Figure 3-2 Retardation of recrystallization by the microalloying elements.

This alloy design therefore offers a number of economical processing advantages over traditional grades, particularly API high strength grades, as pointed out by Ouaissa et al. [27].
 a) Continuous casting can be successfully achieved over an increased slab width range providing greater tonnage throughput at slab making operations.
 b) Hot ductility is improved and so slab-cracking issues are avoided. This not only avoids the necessity for slab inspections and reconditioning but also provides the opportunity to reduce energy consumption by direct hot charging.
 c) Increased thermal processing window enables more significant slab width reductions at the sizing press.
 d) Finish rolling temperature is increased, i.e. T_{nr} is raised, and so entry to finishing mill is increased by roughly 100ºC and so provides latitude for increased reductions & / or reduced mill loadings, thus minimizing mill wear and tear.

In summary the alloy design permits steel mills with low installed rolling forces to produce high strength steel grades with enhanced toughness [26]. The weldability performance of these steels therefore needs to be more thoroughly understood.

Despite the wide ranging research [28-30] carried out on the role of Nb in steel there is relatively limited work on the effect of increased Nb concentration on weld HAZ grain size control in these low carbon steels. Therefore this experimental work was conducted to investigate the effect of Nb and C content on austenite grain coarsening in thermal cycles similar to that experienced in the HAZ of a typical fusion weld. The chemical composition of the studied steels is presented in Table 3-1.

Table 3-1 Chemical composition (key alloy elements) of the investigated steels, in wt%.

Steels	C	Mn	Si	Mo	Cr	Nb	Ti	V	N
Steel 1	0.14	1.2	0.27	0.002	0.02	0.001	0.014	0.006	0.0021
Steel 2	0.085	1.44	0.3	0.01	0.03	0.033	0.016	0.066	0.006
Steel 3	0.047	1.59	0.23	0.15	0.031	0.055	0.0077	-	0.0031
Steel 4	0.05	1.61	0.16	0.002	0.24	0.11	0.012	0.003	0.0048

6

Three different Nb bearing steels were selected, along with a Nb free steel, all of which contained Ti, and subjected to four different peak temperatures (1050, 1150, 1250 and 1350˚C) using a Gleeble 3500 thermal-mechanical simulator. The heating rate, dwell time and cooling rate, which are presented in Figure 3-3, were selected to duplicate typical thermal conditions experienced during actual weld fabrication, but in any case were identical for each steel.
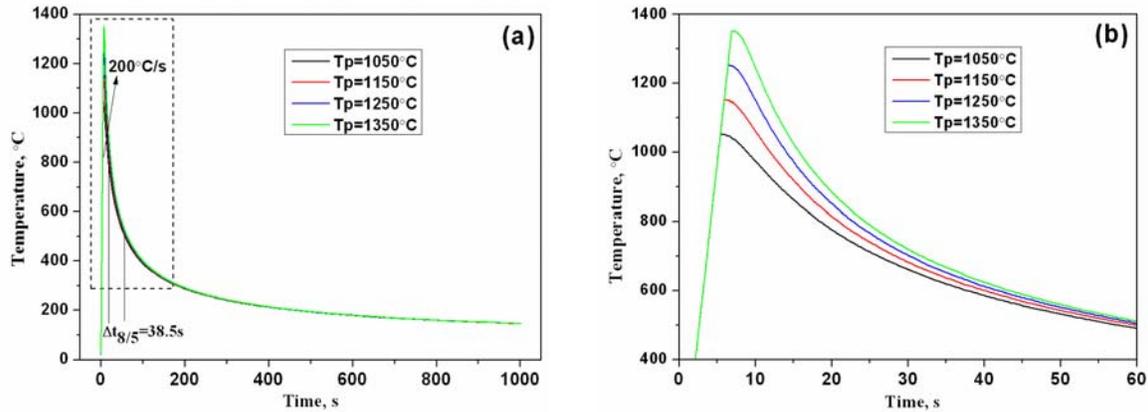

Figure 3-3 Thermal cycles used for the HAZ simulation of the studied steels: (a) overview; (b) close-up.

The average austenite grain size values of the four investigated steels are presented in Figure 3-4. Measured grain size of the samples subjected to thermal cycle with peak temperature of 1050˚C was fairly uniform with average value of ~10 μm. Increasing peak temperature to 1150˚C resulted in significant grain growth in the Nb free steel. A peak temperature of 1250˚C stimulated grain growth in all four steels but interestingly, the high Nb steel experienced a rapid increase in grain size, in comparison to 1150˚C. As peak temperature increased to 1350˚C, significant coarsening occurred in all steels except the high Nb steel, where only a slight increase occurred.

Overall, the Nb-containing steels exhibited greater austenite grain size control compared to Nb free grade while the high Nb, low C steel demonstrated remarkable control at the peak temperature of 1350˚C.
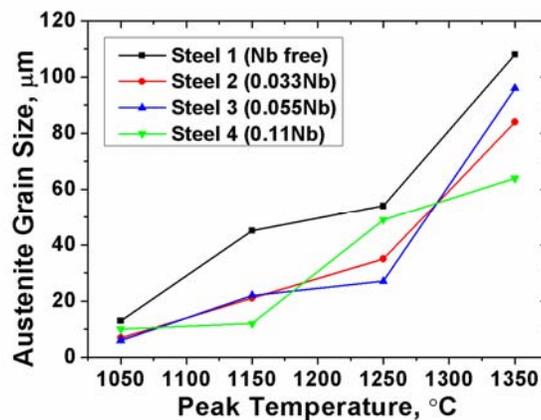

Figure 3-4 Grain size measurements of the investigated steels at different peak temperatures.

In weld thermal simulation trials where the $\Delta t_{8/5}$ cooling time was varied to simulate differences in weld heat input, in Figure 3-5 the data confirmed that the extent of thermal degradation in the high Nb steel was significantly less than that compared with the conventional Nb bearing Steel 2 & Steel 3. Further evidence of the remarkable performance of the high Nb steel is revealed in Figure

3-6 where the Charpy impact transition temperature is approximately 20ºC lower than Steel 3 which can be attributed to the finer grain size and uniform CGHAZ microstructure in Figure 3-7.

These results demonstrate the ongoing technical development that underpins the increasing versatility of steels in our society and the diligent use of microalloying to improve steel performance.
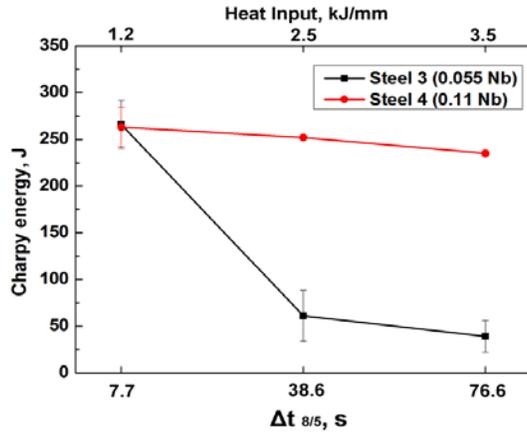

Figure 3-5 Comparison of Charpy impact toughness (at -20˚C) of Steel 3 and Steel 4 steel as function of (Δt8/5) weld cooling time, which can be correlated with weld heat input.
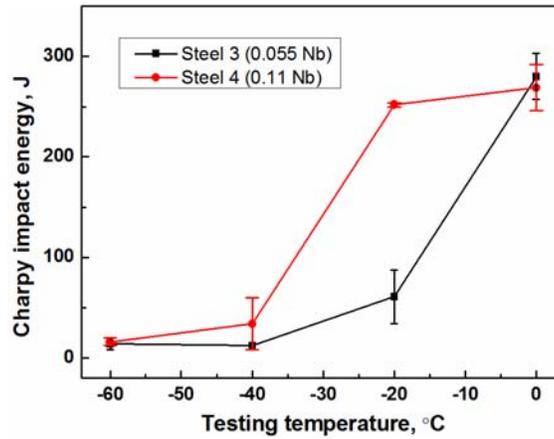

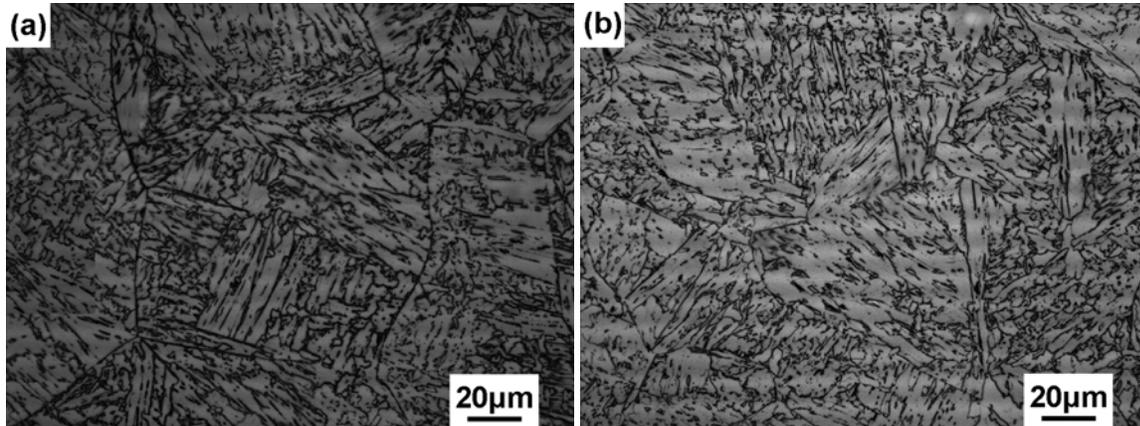Figure 3-6 Ductile brittle transition curves for Steel 3 and Steel 4.

Figure 3-7 Representative photographs of microstructure for simulated CGHAZ: (a) Steel 3 (0.055 Nb); (b) Steel 4 (0.11 Nb).

4   Closing Comments

This paper has reviewed the current technology related to the use of Ti in control of weld HAZ properties in high strength steels. The additional results presented have served to highlight the influence of Nb content on grain coarsening characteristics and weldability.

Interestingly, all investigated steels contained deliberate additions of Ti that is known to restrict austenite grain coarsening at high temperatures but the role of high Nb and low carbon in this work has demonstrated an unexpectedly beneficial effect.

Nb-Ti microalloyed steels are known to contain complex precipitates which can include (Ti,Nb)(C,N), some can exist as a Ti-rich core & Nb-rich shell structure [31] and others as separate precipitates.

It is also well known that the dissolution of Nb rich precipitates in these steels occurs at a lower temperature than that of Ti, particularly when TiN exists. The fact that the high Nb steel demonstrated superior austenite grain size control at 1350ºC and enhanced fracture toughness in simulated coarse grained HAZ, presents an exciting opportunity that could further incrementally improve the weldability and structural integrity of fabricated structures produced from high strength steels.

The mechanism for this performance could be related to a number of different effects which include, but not limited to :

- Solute drag effects from the presence of Nb in solid solution, from dissolution of NbC & NbCN,
- the role of Nb rich shell surrounding TiN precipitates, forming a barrier to the coarsening of TiN precipitates,
- segregation of Nb to austenite grain boundaries [32] and/or decreasing grain boundary energy [33], which can thus retard grain growth.

It is clear that these recent results present an exciting opportunity to further improve the reliability of modern high strength steels and warrants further investigation which is the subject of ongoing studies at the University of Wollongong.

5   Acknowledgements

6   References

1.   Pickering, F. *Titanium nitride technology*. in *35th mechanical working and steel processing conference*. 1993. Pittsburgh, Pennsylvania, USA.

2.   Gladman, T. and D. Dulieu, *Grain-Size Control in Steels*. Metal Science, 1974. **8**(1): p. 167-176.

3.   Batte, A., P. Boothby, and A. Rothwell. *UNDERSTANDING THE WELDABILITY OF NIOBIUM-BEARING HSLA STEELS*. 2001.

4.   Bateson, P., et al., *Development of TMCR steel for offshore structures*. Structural Materials in Marine Environments, 1994: p. 226-243.

5.   George, T. and J. Irani, *Control of austenitic grain size by additions of Titanium*. J AUST INST METALS, 1968. **13**(2): p. 94-106.

6.   Barbaro, F. and P. Krauklis. *Intragranular ferrite in inoculated low-carbon steels*. in *Materials Forum*. 1995.

7.   Smith, C.S., *GRAINS, PHASES, AND INTERFACES: AS INTERPRETATION OF MICROSTRUCTURE*. MET TECHNOL, 1948. **15**(4): p. 1-37.

8.   Loberg, B., et al., *The Role of Alloy Composition on the Stability of Nitrides in Ti-Microalloyed Steels during Weld Thermal Cycles*. Metallurgical and Materials Transactions A, 1984. **15**(1): p. 33-41.

9.   Matsuda, S. and N. Okumura, *Effect of Distribution of Ti Nitride Precipitate Particles on the Austenite Grain Size of Low Carbon and Low Alloy Steels*. Trans. Iron Steel Inst. Jpn., 1978. **18**(4): p. 198-205.

10.   Fairchild, D., D. Howden, and W.A.T. Clark, *The Mechanism of brittle fracture in a microalloyed steel: part I. Inclusion-induced cleavage*. Metallurgical and Materials Transactions A, 2000. **31**(3): p. 641-652.

11.   Fairchild, D., D. Howden, and W.A.T. Clark, *The mechanism of brittle fracture in a microalloyed steel: Part II. Mechanistic modeling*. Metallurgical and Materials Transactions A, 2000. **31**(3): p. 653-667.

12.   Bang, K.S. and H.S. Jeong, *Effect of nitrogen content on simulated heat affected zone toughness of titanium containing thermomechanically controlled rolled steel*. Mater. Sci. Technol., 2002. **18**: p. 649-654.

13.   Smaill, J.S., S.R. Keown, and L.A. Erasmus, *Effect of titanium additions on the strain-aging characteristics and mechanical properties of carbon-manganese reinforcing steels*. Met. Technol., 1976: p. 194-201.

14.   Bang, K.-s., C. Park, and S. Liu, *Effects of nitrogen content and weld cooling time on the simulated heat-affected zone toughness in a Ti-containing steel*. Journal of Materials Science, 2006. **41**(18): p. 5994-6000.

15.   Wang, S.-C., *The effect of titanium and nitrogen contents on the microstructure and mechanical properties of plain carbon steels*. Materials Science and Engineering: A, 1991. **145**(1): p. 87-94.

16.   Choi, J.K. *Development of high strength and high performance steels at POSCO through HIPERS-21 project*. in *1st Int. Conf. on 'Super-high strength steels'*. 2005. Rome, Italy: Associazione Italiana di Metallurgia.

17.   Zhu, Z., et al., *Influence of Ti/N ratio on simulated CGHAZ microstructure and toughness in X70 steels*. Science and Technology of Welding and Joining, 2013. **18**(1): p. 45-51.

18.   Zhu, Z., et al., *Influence of Ti/N ratio on simulated CGHAZ microstructure and toughness in X70 steels*. 2012.

19. Bowie, G.F., et al., *The influence of micro titanium additions on the weld heat affected zone hardness of C-Mn structural steels*, in *International Conference Welding 90*. 1990: Geestacht. p. 219.

20. Gray, J.M., *Transformation Characteristics of Very-Low-Carbon Steels*, F.J. Barbaro, Editor. 1969: Wollongong.

21. Ji, L., et al., *Research on key technology and production quality of X80 linepipe for the 2nd West-East gas pipeline*, in *International Seminar on X80 and Higher Grade Line Pipe Steel*. 2008: Xi'an, China.

22. Fazackerley, W.J., P.A. Manuel, and L. Christensen. *First X-80 HSLA Pipeline in the USA*. in *Proc. International Symposium on Microalloyed Steels for the Oil and Gas Industry*. 2006. Araxa, Brasil.

23. Hulka, K. and J. Gray. *High Temperature Processing of Line Pipe Steels*. 2001.

24. Mohrbacher, H., *GRAIN SIZE CONTROL BY NIOBIUM MICROALLOYING IN GEAR STEEL DURING HIGH TEMPERATURE CARBURIZING.*

25. Vervynckt, S., et al., *Austenite Recrystallization–Precipitation Interaction in Niobium Microalloyed Steels.* ISIJ International, 2009. **49**(6): p. 911-920.

26. Hulka, K., P. Bordignon, and G. Malcolm, *Experience with Low Carbon HSLA Steel Containing 0.06-0.10 Percent Niobium*, in *International Seminar The HTP Steel Project*. 2003: Araxá, Brasil.

27. Ouaissa, B., et al. *Investigations on microstructure, mechanical properties and weldability of a low-carbon steel for high strength helical linepipe*. in *Proceedings of the 17th JTM*. 2009. Milan, Italy.

28. Palmiere, E., C. Garcia, and A. De Ardo, *Compositional and microstructural changes which attend reheating and grain coarsening in steels containing niobium.* Metallurgical and Materials Transactions A, 1994. **25**(2): p. 277-286.

29. Cuddy, L. and J. Raley, *Austenite grain coarsening in microalloyed steels.* Metallurgical and Materials Transactions A, 1983. **14**(10): p. 1989-1995.

30. ALOGAB, K., D. MATLOCK, and J. SPEER, *Abnormal Grain Growth During Heat Treatment of Microalloyed-Carburizing Steel.*

31. Craven, A., et al., *Complex heterogeneous precipitation in titanium-niobium microalloyed Al-killed HSLA steels--I.(Ti, Nb)(C, N) particles.* Acta Materialia, 2000. **48**(15): p. 3857-3868.

32. Essadiqi, E. and J.J. Jonas, *Effect of deformation on the austenite-to-ferrite transformation in a plain carbon and two microalloyed steels.* Metallurgical and Materials Transactions A, 1988. **19**(3): p. 417-426.

33. Vynokur, B., *Influence of alloying on the free energy of austenitic grain boundaries in steel.* Materials Science, 1996. **32**(2): p. 144-157.