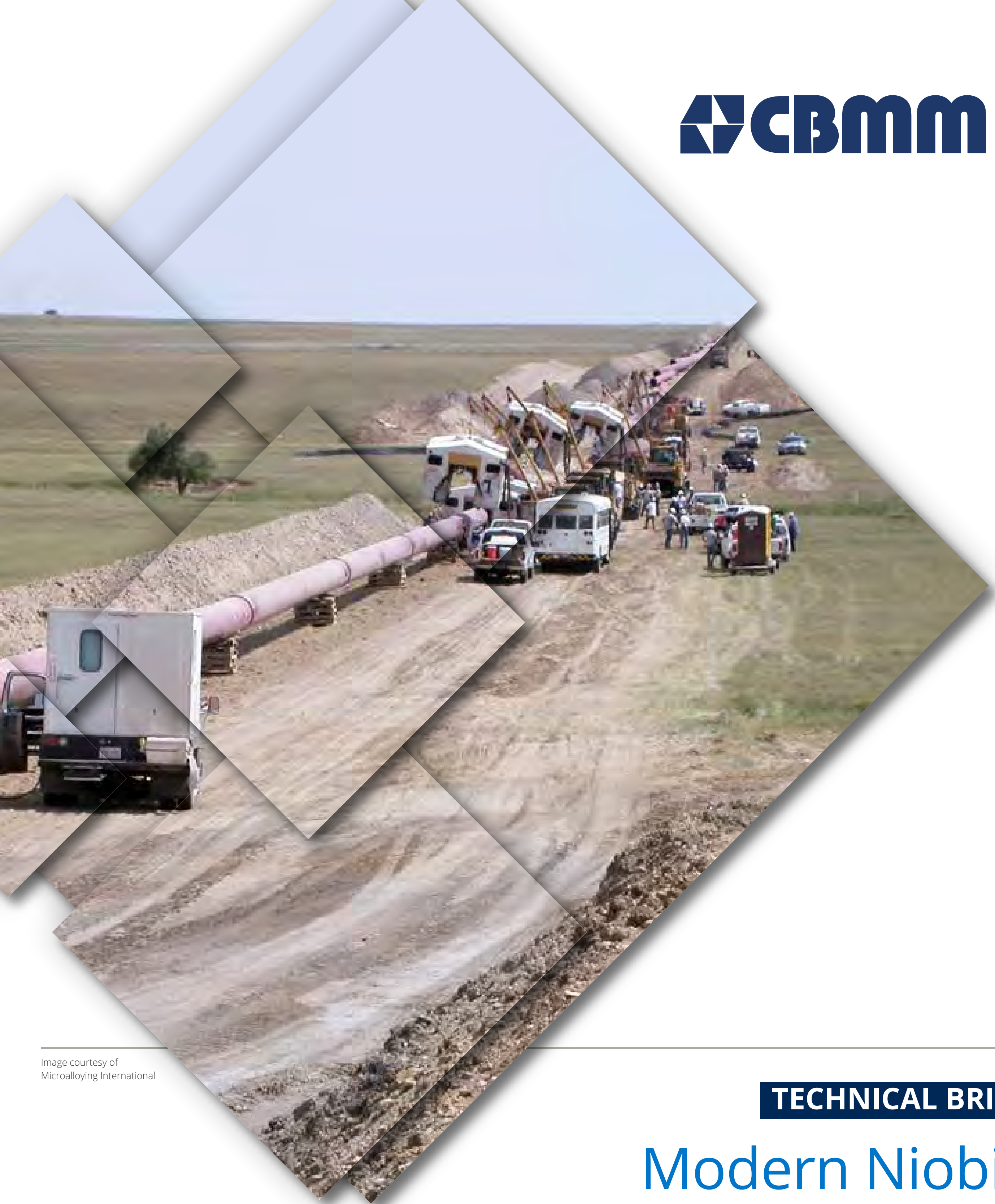

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Microalloying International

TECHNICAL BRIEFING

Modern Niobium Microalloyed Steels and their Weldability

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The principal purpose of this short document is to provide the reader with basic information about the concept of weldability, and its importance to the fabrication industry. Whilst much of the content is general in nature the following information focuses on the fabrication of steels containing niobium. Niobium is added during the steelmaking process as a ferroniobium addition and its presence in steels, at very modest levels, significantly increases both strength and toughness, bringing benefits in a range of sector applications worldwide. Welding is, inevitably, an essential feature of the manufacture and use of virtually all steel products.

Niobium plays an important role, world wide, in many steel types including stainless steels, which are not dealt with in this document but its major application is in what are commonly referred to as high strength low alloy steels (HSLA); these are also often referred to as microalloyed steels. Such steels find application in many different product forms such as plates, beams, wire rods and pipes etc., but perhaps the most important sectors are sheet for the car industry and plate or coil for the manufacture of higher strength oil and gas transmission pipes.

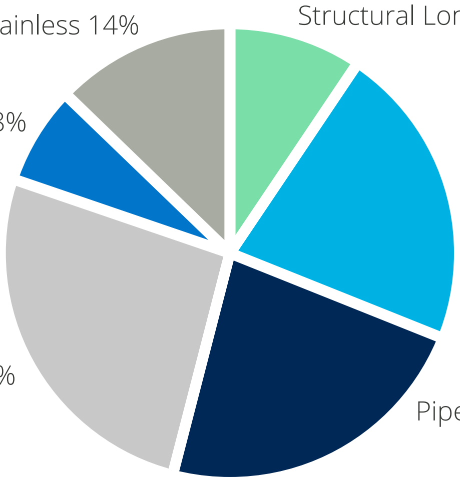

Figure 1. Distribution of ferroniobium by sector application – 2015 data (source CBMM).

Historically from the late 1950's and through the sixties and seventies carbon manganese (C-Mn) microalloyed steels would have contained niobium levels in the range 0.015 to 0.04 weight percent. However, with improvements in modern steelmaking using cost competitive production processes, reductions in carbon content down to 0.06 percent or even lower, and an enhanced understanding of the enormous potential of niobium as a microalloying element, it is now not uncommon for steelmakers to employ up to 0.11 percent niobium to provide products with superior properties and, as we will see later, improved weldability.

What is a weld and what do we mean by the term weldability?

A weld is simply the joint between two pieces of material and involves the heating of the separate pieces to a temperature above their melting point. This usually involves the application of an electric current to an electrode which melts both the electrode itself and the adjacent surfaces to be joined. The weld is usually, therefore, comprised of a mixture of the material being welded and the filler electrode.

Welds can be single pass or multi pass as indicated below.

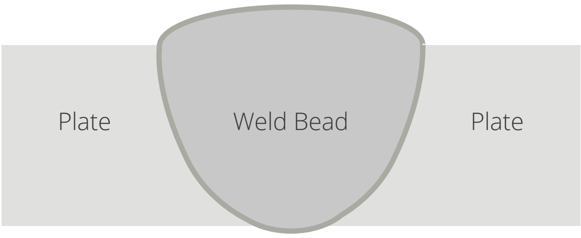

Figure 2. Single pass weld.

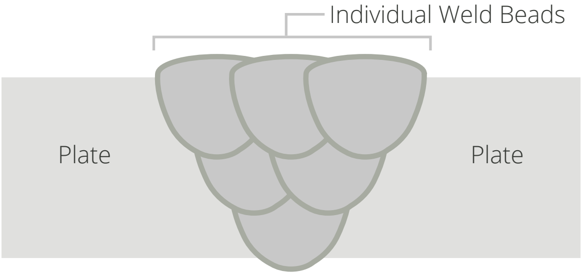

Figure 3. Multi pass weld.

The thermal cycles experienced by the material being welded result in very rapid heating and cooling and the precise nature of the cycle can influence the weld metal properties and those of the adjacent heat affected zone (HAZ). Clearly the material melted into the weld metal, through what we refer to as dilution, may influence its chemical composition and thus its microstructure and properties. In the HAZ it is the chemical composition and ability to resist grain coarsening which primarily control the microstructure.

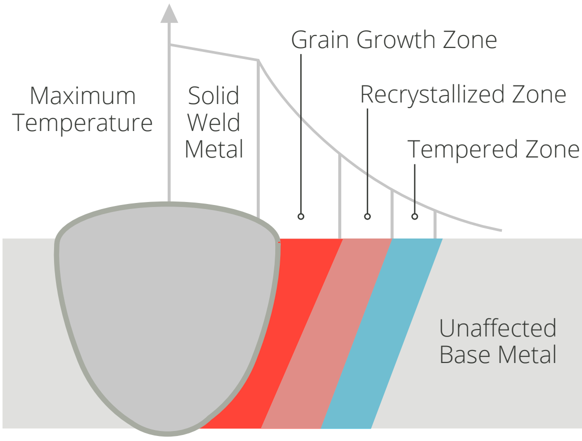

Figure 4. Simplified Heat Affected Zones.
(Adapted from Easterling) [1].

What about weldability?

In its simplest definition the word just relates to the ease with which a material can be reliably and safely joined by welding. A more comprehensive technical definition is as follows:

The ability of a material to be joined using a wide range of appropriate welding processes to produce joints effectively free from significant defects and strong enough and tough enough, in all areas of those joints, to be fit for the purpose intended [2].

There are very many aspects of steel weldability and some of the problems which were commonplace decades ago are no longer very often encountered because of the wider availability of advanced, clean, steelmaking processes leading in particular, to lower sulfur and phosphorous levels [2]. However, the most significant progress has come from the realization that lower carbon levels, usually in conjunction with lower carbon equivalents (CE), are a precursor for optimum weldability.

So where does niobium fit in?

Interest in the possible influence of niobium on weldability tends to be focused on three particular areas:

(i). Its effect on weld metal microstructure and toughness;

(ii). Its effect on hydrogen induced cold cracking (as defined later);

(iii). Its effect on HAZ microstructure and toughness.

So let us look at each of these in turn.

Weld Metal and Niobium

When a weld is made as described earlier, it is generally referred to as a fusion weld and, depending on the energy of the arc i.e. its heat input, a percentage of the final weld metal is derived from material melted into the weld pool from the steel being welded. Some welds might be described as high dilution and some as low dilution as below.

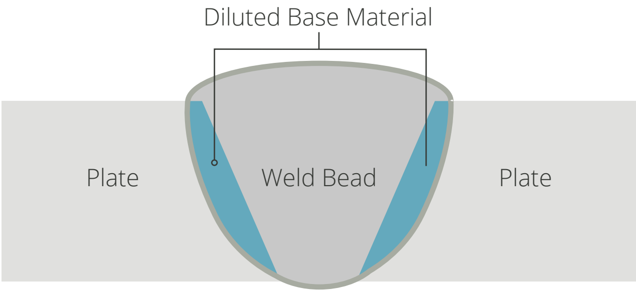

Figure 5. Illustration of the concept of dilution.

Dilution % = (area of diluted base metal ÷ total of fused area) x 100

The extent of the dilution experienced is usually dependent on the welding process. Multi arc welds, applied in pipe mills for example, are made using the submerged arc process and will tend to have a higher combined electrical energy input and will therefore exhibit higher dilution, whilst lower energy manual metal arc welds made with 'stick' electrodes, will result in significantly lower dilution. Appendix 1 illustrates the key features of the most common welding processes.

Since elements diluted into the weld pool contribute to the final chemical composition of the solidified weld, they can be expected to have some influence on the weld metal's microstructure and its mechanical properties, namely strength and toughness. However, the cooling rate of the weld is also of critical importance and this depends on the energy input and the thickness of the steel being welded.

Elements such as carbon, manganese and nickel often have a dominant effect on weld metal properties and where difficulties are encountered, they are often attributable to the carbon level of the completed weld being too high. We refer to such elements as promoting higher hardenability which in effect, means that they cause the final microstructure of the weld metal to form at a lower temperature. This may be good or bad depending on the precise balance of the elements present. Appendix 2 provides additional clarification of the term 'hardenability'.

Niobium also has an almost uniquely powerful ability to act, in some circumstances, as an element which can increase hardenability and if it is diluted into solidifying weld metal, its effect can be beneficial so long as the carbon level of the weld is kept below about 0.1 percent.

Indeed, by judiciously harnessing niobium's effect, the level of alternative hardenability elements such as manganese and nickel can be greatly reduced preventing over hardening and the occurrence of reduced toughness.

In future we may even see the development of welding electrodes that deliberately set out to increase weld metal niobium levels.

Hydrogen Induced Cold Cracking

The carbon equivalent (CE) of a steel is often used as an approximate guide to its hardenability [2] and its ability to resist one of the most common problems in fabrication namely hydrogen cracking.

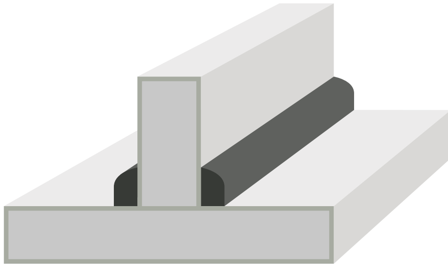

Figure 6. T-fillet welded joint.

Figure 7. Typical hydrogen induced cold crack in a T-fillet weld.

Many different formulae are used to calculate a steel's CE but the most common is probably:

$$CE = C + \frac{Mn}{6} + \frac{(Cr+Mo+V)}{5} + \frac{(Cu+Ni)}{15}$$

Historically, CE values > 0.45 were considered to be undesirable, making the steel more difficult to weld without experiencing hydrogen cracking, whilst levels <0.40 were usually acceptable. However, although this is a good guide, it is an over simplification and it has been realized now, for many years, that it is carbon which is the dominant element and that if its level can be reduced below about 0.1%, acceptable resistance to hydrogen cracking will be achievable almost irrespective of CE level [3].

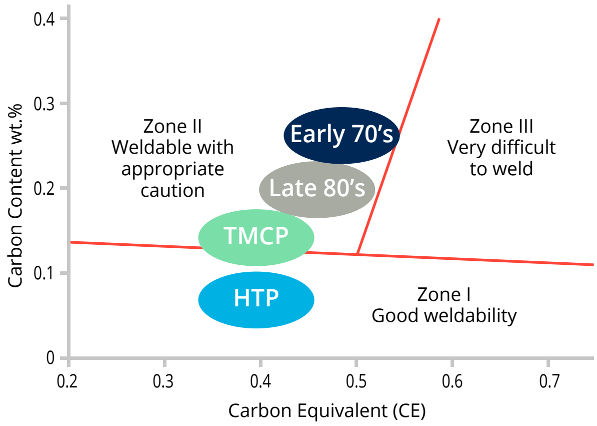

Figure 8. The evolution of carbon and carbon equivalent in recent decades (adapted from Graville) [3].

It is noteworthy that niobium doesn't feature in any of the common CE formulae and experience confirms that it doesn't have any adverse effect on hydrogen induced cold cracking. Indeed, if anything, it improves a steel's performance in this context [4]. In simple terms this improvement comes about because, with fast thermal cycles during welding, niobium rich precipitates restrict grain growth in the HAZ resulting in a better microstructure (without hard martensite). This benefit applies to all niobium treated steels irrespective of processing route but is optimized in steels with carbon below about 0.06% and niobium above 0.07%.

Heat Affected Zone Toughness

The area of plate immediately adjacent to a solidifying weld is actually an extremely complex zone and consists of many sub zones the details of which are adequately addressed elsewhere [5] however for the purposes of this guide, we will assume that the area known as the coarse grained heat affected (CGHAZ) zone is most important.

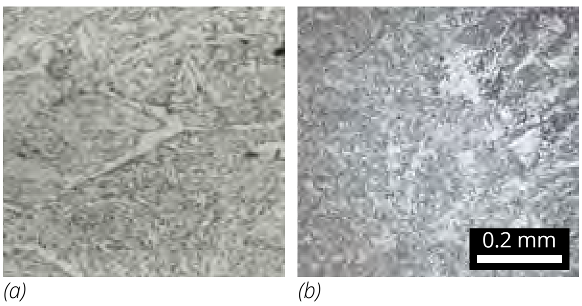

Figure 9. Contrast in CGHAZ growth between conventional (a) and HTP steel (b).

Many of the most advanced niobium treated steels also contain a very small level of titanium which, through precipitation, works in conjunction with niobium to provide even better grain coarsening resistance.

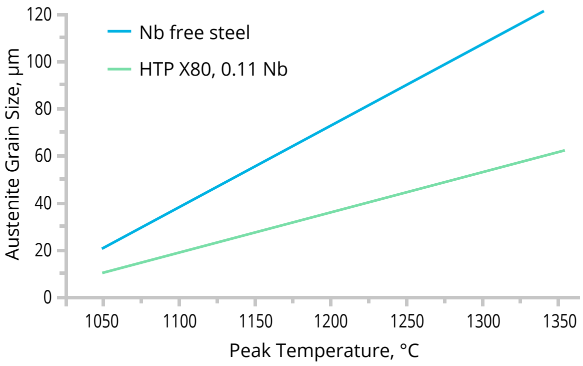

Figure 10. Schematic effect of niobium on HAZ grain coarsening characteristics.

Finer grain sizes in the HAZ almost invariably result in improved microstructure and toughness and, at lower heat inputs, it is the fine distribution of niobium rich precipitates (as described in the preceding section) which play the key role. Fine grain size, for a given chemical composition, tends to reduce what we earlier referred to as hardenability and this means that lower temperature transformation products such as martensite, which might be brittle, can be avoided.

As heat input increases, the niobium treated steels continue to resist grain growth which we have already noted. This tends to be good for toughness but, since finer grain sizes also promote lower hardenability, it might be expected that at some point, as cooling rates decrease in response to higher heat inputs, the transformation temperature may not be low enough to develop an appropriate microstructure to maintain optimum toughness. However, interestingly, and surprisingly to many, is the fact that any adverse transformation effect resulting from the smaller grain size, is counterbalanced as heat input increases by a second important effect, which is unique to niobium.

As the fine niobium precipitates, which are restricting grain growth, begin to dissolve and the niobium released enters solution, it begins to exert its well documented and powerful effect on hardenability. This positive effect ensures that transformation temperature remains low enough to generate the formation of a relatively fine grained tough bainite over a very wide range of heat inputs, and thus cooling rates.

Martensite is the lowest temperature transformation product encountered in steel weld heat affected zones. Its hardness is dictated by its carbon content and the higher the carbon content the more likely it is that the martensite will exhibit poor toughness. Bainite is the name given to the microstructure often encountered in the CGHAZ of HSLA steels and, if chemistry is optimized with low carbon content, its combination of strength and toughness is remarkable.

Fine grained bainitic microstructures in low carbon, higher niobium steels provide excellent toughness over a wide range of heat inputs (see Figure 11).

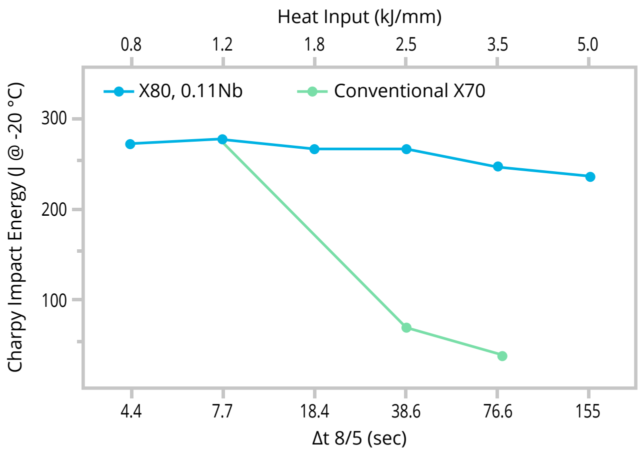

Figure 11. HAZ Charpy impact toughness data from a 0.11% Nb steel directly compared with that from a conventional X70 steel (weld thermal simulation data) [6].

Low carbon, higher niobium HSLA steels with niobium levels of up to at least 0.11 percent have the unique ability to provide this type of optimum microstructure with a wide range of different welding procedures and plate thicknesses.

Conclusion

Niobium is a uniquely important element and its place in modern HSLA steel design is becoming more and more widely appreciated. The advent of lower carbon steelmaking and the realization of the importance of low carbon to steel properties and weldability in particular, is undoubtedly changing opinions. For example, high strength linepipe steels for the most onerous and highest pressure applications are now most likely to be specified in a way which encourages steelmakers, fabricators and their clients to take advantage of our enhanced understanding of the role played by niobium and its specific benefits in lower carbon steels. International standards are also, at last, accepting and recognizing the benefits to be gained by employing a low carbon, higher niobium approach to steel specification for a wide range of important applications.

References

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Appendix 1. Conventional Welding Methods

Figure 12. Manual Metal Arc Welding.

Figure 13. Submerged Arc Welding. (Image courtesy of Tata Steel Tubes)

Figure 14. Gas Metal Arc Welding (Westpath, internal welding of the Gr. 690 using the 4 head, short circuit GMAW [7].)

Appendix 2. Hardenability

When steel is subjected to heating, and when the temperature is progressively raised above 1000 degrees centigrade, it exists in a form we call austenite. The amount of austenite formed depends on composition and heating rate. When the steel is subsequently cooled again the austenite typically transforms back to a mixture of ferrite and various carbon rich phases. The lowest temperature transformation product encountered on cooling is called martensite.

Hardenability is simply the ability of a steel to partially or completely transform from austenite to some fraction of martensite at a given depth below the surface, when cooled under a given condition. For example, a steel of a high hardenability can transform to a high fraction of martensite to depths of several millimeters under relatively slow cooling, such as an oil quench, whereas a steel of low hardenability may only form a high fraction of martensite to a depth of less than a millimeter, even under rapid cooling such as a water quench. Hardenability therefore describes the capacity of the steel to harden in depth under a given set of conditions.

The following are typical microstructures that would be encountered at specific cooling rates as indicated below.

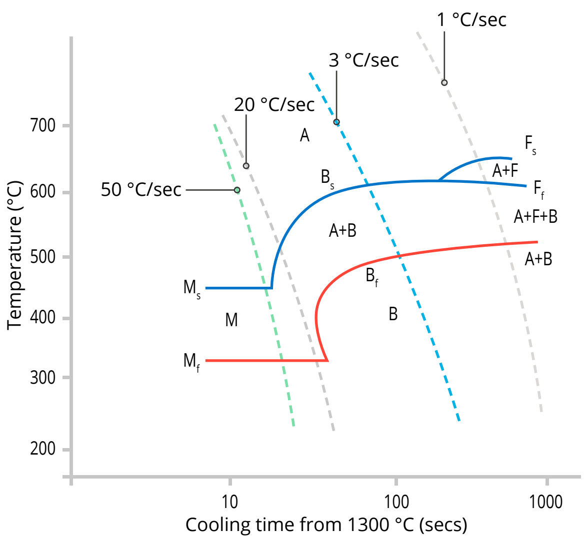

Figure 15. Typical CCT diagram of a niobium microalloyed containing offshore structural steel.

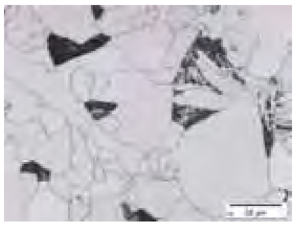

Figure 16. Ferrite and perlite (dark areas) would be observed at cooling rates around 1 °C/sec.

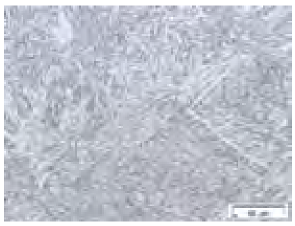

Figure 17. Bainite would be observed at cooling rates between 3 and 20 °C/sec.

Figure 18. Martensite would be observed at cooling rates exceeding about 30 °C/sec.

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