NICKEL STEELS IN ARCTIC SERVICE

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ABSTRACT

This paper presents an overview of nickel bearing steels used for arctic service in the oil and gas industry. The beneficial effects of nickel on fracture toughness at low temperatures, mechanical properties of thick section forgings and enhanced weldability of steels are discussed. Comment is also made regarding the limitation on the use of nickel steels with 1 per cent nickel or higher in sour service, imposed by NACE Standard MR-01-75.

Materials to be examined include nickel steels for structural applications (offshore structures, storage facilities, etcetera) and those specific to oil and gas production.

In addition, the emerging use of highly alloyed nickel-containing materials, such as duplex stainless steels for enhanced corrosion resistance, is addressed.

ARCTIC CONDITIONS AND THE BEHAVIOUR OF STEELS

The most critical factor effecting the behaviour of steels in arctic service is temperature. Temperatures on the order of -50°F (-46°C) or lower may be experienced over prolonged periods of time. This extremely low temperature is below the ductile - to - brittle transition temperature for most carbon-manganese structural steels used for construction and manufacturing of components in the oil field.

Application of steels below their nil ductility temperature (NDT) is avoided because of the danger created by brittle crack propagation, that could lead to catastrophic failure of a component or entire system. Below the NDT very little energy is required for fracture propagation, thus fracture arrest becomes difficult. The key to enhanced fracture toughness on resistance to crack propagation is to use a steel with an NDT below the lowest expected operating temperature.

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Two other factors of importance in selecting materials for the arctic service in the oil and gas industry are corrosion resistance and weldability. The former is not as important for structural applications as for the production and transportation of corrosive oil and gas. Carbon steels have only limited corrosion resistance and must be replaced with corrosion resistant alloys (CRA) when metal loss becomes severe.

Weldability is important when considering the need to retain the enhanced fracture toughness of the base metal used for arctic service. If the weld has inferior toughness, fracture will occur regardless of the quality of the base metal. Therefore, it is essential that the weld metal and heat-affected zone achieve a fracture toughness greater than or equal to that of the base metal. Furthermore, this should be accomplished without preheat and/or postweld heat treatment whenever possible to reduce the cost of welding in the arctic.

ROLE OF NICKEL IN STEELS AT LOW TEMPERATURE

The addition of small amounts of nickel to carbon and low-alloy steels can greatly enhance the notch toughness of these steels especially at low temperatures. Fracture toughness of carbon steel, as measured by Charpy Impact testing, is shown to increase with increasing nickel content, Figure 1. The NDT can be seen to decrease from approximately -80 °F to less than -300 °F for 9% Ni steel.[1] The upper shelf energy is also enhanced by these small additions of Ni, which is related to the increased hardenability of the steel. This additional benefit of increased hardenability will be addressed later.

The data for Figure 1 were generated for normalized and tempered steels. Although many other factors affect the toughness of steel, heat treatment is one of the most important factors. Figure 2 shows the advantage gained in fracture toughness by quenching and tempering versus normalizing and tempering.[2] These data are for a 1.7% Ni steel, whereas, comparing it to a low-alloy steel with no nickel, the effect is even more dramatic.

Since quenched and tempered microstructure provide the best metallurgical structure for fracture toughness, as observed in Figure 2, it is imperative to achieve a fully martensitic microstructure on quenching. The capability of an alloy to achieve this is referred to as hardenability and is related to the speed of quenching (cooling) and the composition of the alloy. As the section thickness of a steel component increases, the ability to quickly cool to form martensite is impaired. To overcome the adverse effect of section size or to allow use of a less severe quench, alloying elements are added to the steel. One of the most important alloying elements for increasing hardenability is nickel. In Figure 3 the hardenability of AISI 4340 is compared to that for AISI 4140, two commonly-used alloys for oilfield applications.[3] The depth of hardening is seen to be greater for 4340 (1.7%Ni) than for 4140 (0%Ni). Therefore, for heavy sections it is easier to achieve the desired hardenability with AISI 4340 than with a similar thickness of AISI 4140.

Hardenability and fracture touchness are factors that go hand-in-hand to create a material of overall superior performance for many applications, especially under arctic conditions.

In addition to these parameters, the use of nickel in conjunction with chromium at higher concentrations may provide greater corrosion resistance for severe environments. Figure 4 shows the effect of nickel in combination with chromium in enhancing the resistance of duplex stainless steel to pitting corrosion.[4] This increased resistance to pitting attack for duplex stainless steels also reflects a greater resistance to stress corrosion cracking of these alloys, compared to ferritic stainless steels and austenitic stainless steels of the same composition as the ferrite/austenite present in the duplex,[5] Figure 5. It is because of this more favourable stress corrosion cracking resistance and reduced localized corrosion rate, that duplex stainless steels have become popular for piping, vessels and valve applications in severely corrosive environments.

Regardless of the improvements nickel offers to alloys for arctic service, if the material must be welded, metallurgical changes from welding may adversely affect the improved properties of the base metal.

Thus, proper electrode selection and welding procedure is necessary to ensure the entire component is suitable for arctic service. As expected, nickel increases the fracture toughness of welds at arctic temperatures as well as at higher temperature.[6] Figure 6 is from data generated for welding the high strength line pipe for the Trans-Alaskan Pipeline. The E70S-6 electrode contains no nickel, however, an addition of only 1.7% Ni significantly increased the fracture toughness even at the upper shelf energy temperatures.

APPLICATION OF NICKEL STEELS

Environmental and economic aspects of operating in arctic regions favours the use of high strength steels. As such, the demand for high strength coupled with excellent fracture toughness often requires the utilization of nickel alloying to achieve these properties.

Recent developments in producing higher strength line pipe grades X80 and X100 suggest the need for both nickel and a quenched and tempered microstructure.[7] Of course, the trend to higher strength line pipe will involve the need for high toughness welds and, therefore, the inclusion of nickel in the welding electrodes.

An alloy specifically designed for pipelines and offshore structures in the arctic is IN-787. This Ni-Cu-Nb steel (nominally 0.9% Ni) has excellent toughness at low temperatures. When welded with nickel-containing electrodes (1.6 to 2.4% Ni), it exhibits good low temperature properties down to -50°F,[8] as shown in Figure 7. IN-787 has also been considered for use in Christmas tree valve manufacturing, because of its low temperature toughness.

Another alloy proposed for valve bodies is ASTM A352 Grade LC2-1. This alloy contains 3% Ni and possesses excellent fracture toughness under arctic conditions when quenched and tempered as expected from the earlier discussion on hardenability and toughness.[9] Figure 8 shows the impact properties of 3% Ni steel in sections ranging from 1 inch to 5 inch thickness.

There is an increasing need for higher pressure wellhead components in the arctic to maintain the high working pressure of new deep wells. To obtain the necessary properties, the valve typically must be heavy wall and the alloy must have adequate hardenability to achieve the desired properties. Thus, nickel bearing steels offer the optimum for heat treatability and increased fracture toughness at high strength.

Besides the fracture toughness consideration, corrosion resistance is often necessary in the arctic. Recently, SOHIO selected a 2205 duplex stainless steel (UNS 31803) for pipelines and flowlines in the Endicott Field of Alaska.[10] This choice was made because of the high corrosion resistance of duplex stainless steels, their excellent low-temperature fracture resistance and welds of equivalent properties when welded with 7-9% nickel containing electrodes.

It is apparent that nickel can be quite beneficial as an alloying element in steels especially at small concentrations in low alloy steels. However, the use of nickel in these steels is currently limited to less than 1% when the steel is exposed to sour gas or oil as per NACE MR-01-75.[11]

LIMITATIONS IMPOSED
BY NACE MR-01-75

Currently, this specification restricts the nickel content of steels to less than 1% if the environment is sour (containing H_2S) at levels defined in the document.(ref. 11) This restriction is based on early laboratory work and experience in the oil industry, that reflected a detrimental effect of Ni on resistance to SSC,[12] see Figure 9. However, this effect was by no means conclusive and a controversy ensued that remains over whether, in fact, there is an effect of Ni on SSC, if Ni changes the mechanism of cracking from SSC to anodic stress corrosion cracking or if Ni does not participate at all. A recent review suggests that sufficient control over important metallurgical variables was not maintained in earlier work to fully establish whether there is an effect.[13] Yet, new evaluations of the role of Ni on SSC still produce divergent views. (ref. 14, 15)

The resolution of this controversy is quite important to the future of oil and gas production in arctic service since the restriction on Ni content severely limits the alloys that may be used for heavy wellhead sections and welded pipeline. The result of this restriction is increasing the cost to produce oil and gas, and ultimately it affects the economics of recoverable reserves. Thus, the actual role of Ni in SSC needs to be elucidated based on sound metallurgical principles and the limitations of MR-01-75 reviewed in light of more recent studies.

CONCLUSIONS

Alloying of low alloy steels and weldments with up to 3% Ni can significantly improve fracture toughness under arctic conditions. Furthermore, improvement in fracture toughness is often linked to hardenability for which Ni is also effective. Nickel containing duplex stainless steels are also becoming a major contender for corrosion resistant steels in the arctic.

Currently the major limitation to the application of nickel containing low alloy steels is the restriction in NACE MR-01-75 for sour service. Re-evaluation of this restriction should be made in light of more recent work to determine if indeed it is justified since it imposes a serious engineering and economic constraint on oil and gas production in the arctic.

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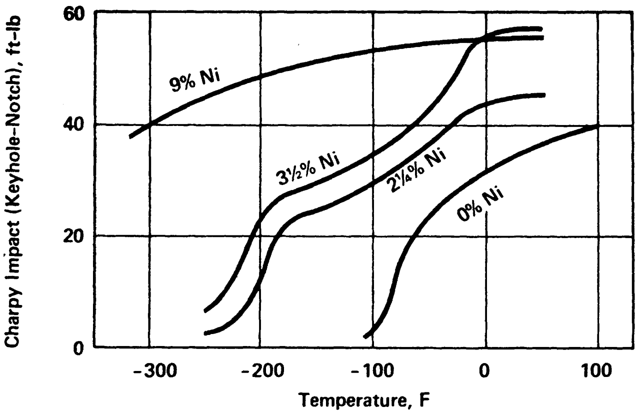

Figure 1 - Effect of nickel on toughness of normalized and tempered 0.5 inch plates of carbon steel. (1)

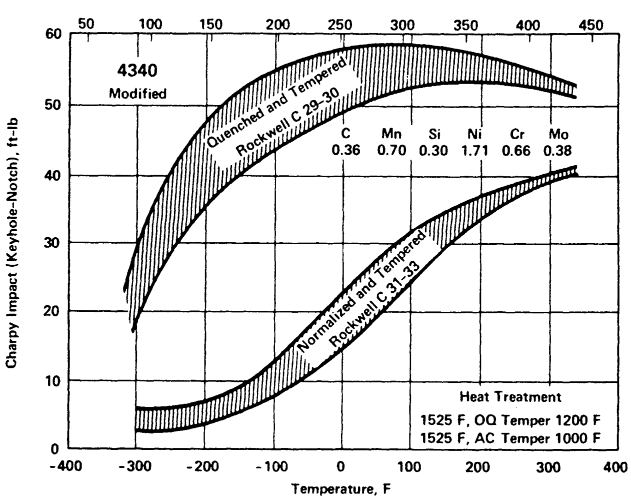

Figure 2 - Effect of heat treatment on impact energy of modified 4340 steel (1.7% Ni). (2)

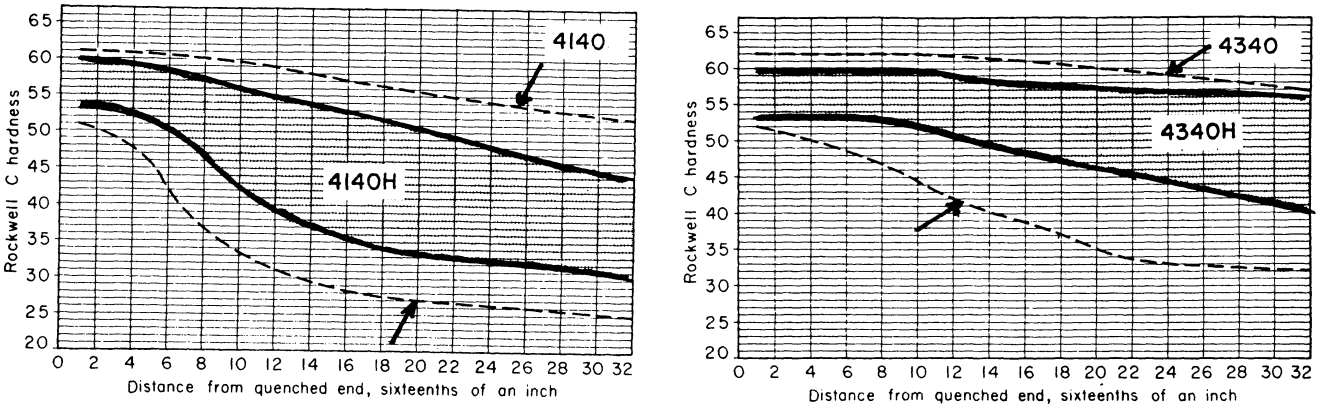

Figure 3 - Comparison of 4140 (0% Ni) and 4340 (1.7% Ni) hardenability, including for restrictive H compositions. (3)

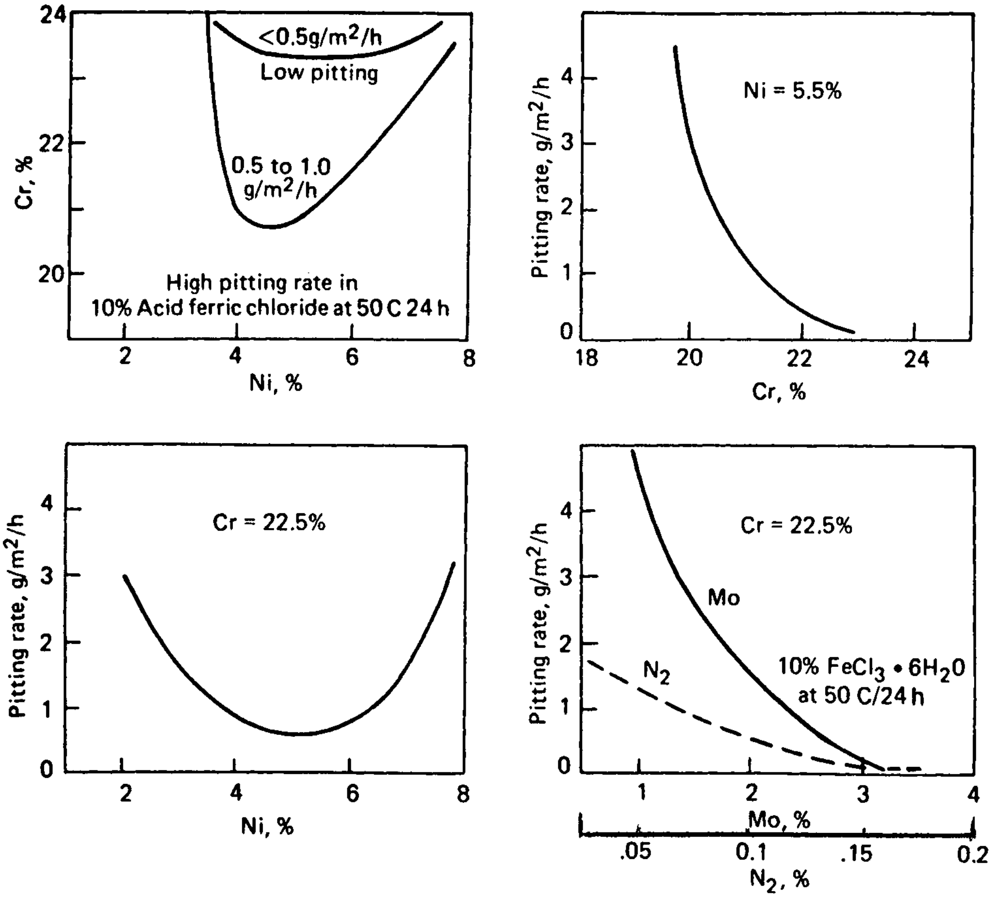

Figure 4 - Optimization of Ni, Cr, Mo and N_2 content in duplex stainless 2205 on pitting resistance in 10% $FeCl_3.6H_2O$ at 50°C for 24 hours. (4)

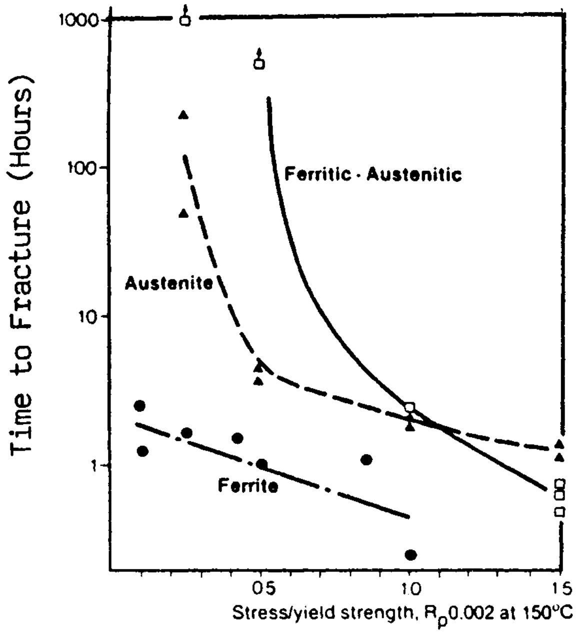

Fig. 5 - Constant load tests of duplex SS and alloys with corresponding α and γ phase compositions in boiling $MgCl_2$. (5)

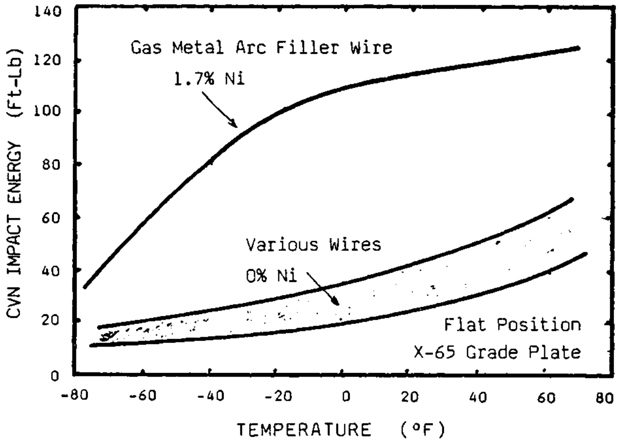

Fig. 6 - Impact toughness of gas metal arc filler wires on X-65 plate. (6) 1.7% Ni wire versus E70S-6 (0% Ni)

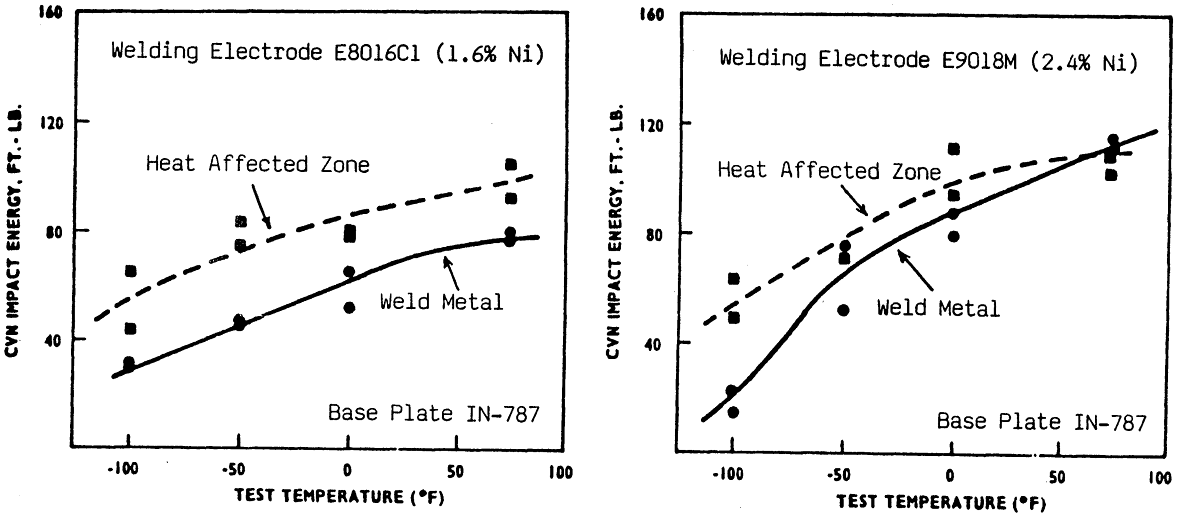

Figure 7 - Charpy impact properties of coated electrode welds (½ inch), No post weld heat treatment. (8)

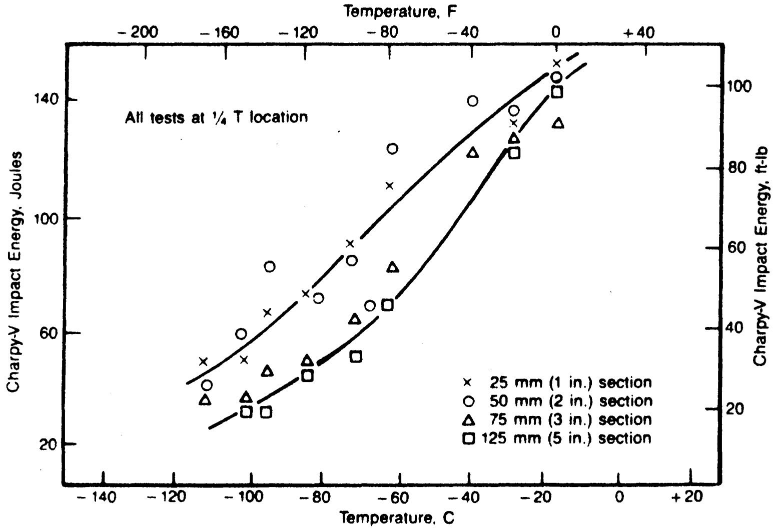

Figure 8 - Fracture toughness of ASTM A352 Grade LC2-1, Quenched and tempered. (9)

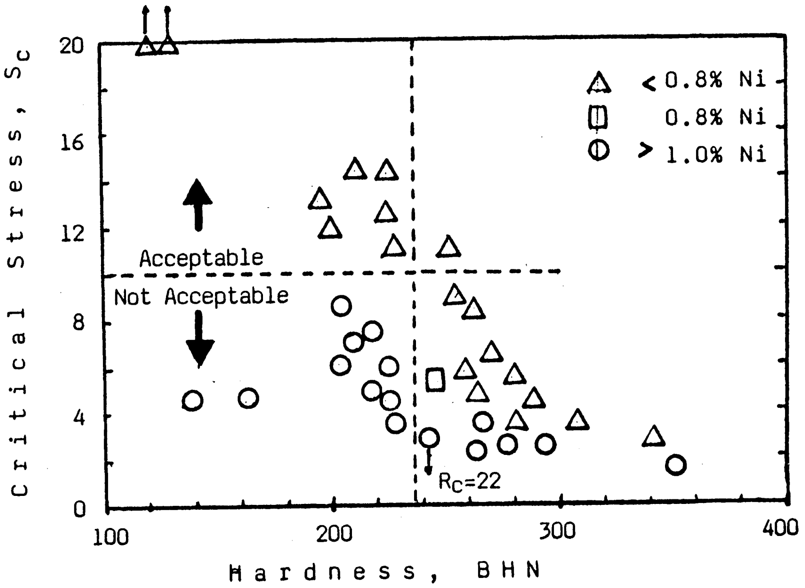

Figure 9 - Effect of nickel content on sulfide stress cracking susceptibility. (11)