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Proposed Modification to Schaeffler Diagram for Chrome Equivalents and Carbon for More Accurate Prediction of Martensite Content

A modified diagram is proposed that takes into account the effects of chromium equivalents ≤ 18% and carbon >0.1%

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ABSTRACT. The austenitizing effect of carbon strongly alters the microstructure of Cr-Ni steels, which is not taken into consideration by the Ni equivalent in the Schaeffler diagram. By determining the austenitizing effect of carbon and the alloying elements, a mathematical formula was devised to calculate a new nickel equivalent, denoted as Ni_{eqB}. On the basis of this, the Schaeffler diagram can be improved. A new regression equation was constructed that gives a good estimation of the measured M_s temperatures. It was concluded that M_s temperatures for the hardenable high-alloy creep-resistant steels, depending on the composition of the steel heats, vary over a wide range. That is why the crack sensitivity of weld metal changes strongly during the welding operation.

Introduction

The Schaeffler diagram is very important to the welding engineer since this diagram helps to determinate the microstructure of the welds made of austenitic Cr-Ni steels. The Schaeffler diagram is normally used for predicting ferrite in stainless steel weld metal (Refs. 1, 2), but the base metal is located in the diagram as well.

The chromium equivalent of corrosion-resistant steels usually exceeds 18%, therefore, investigations have been carried out for improvement of this part of the diagram. As a result of scientific work by Olson (Ref. 3) and Kotecki and Siewert (Ref. 4), this section of the diagram can be considered accurate.

The region of the Schaeffler diagram with less than 18% chromium equivalent has been hardly investigated. Olson derived a formula for calculation of M_s temperature of stainless steels from their composition, but little has been done beyond that.

It should be emphasized that stainless steels have very low carbon content, and the Schaeffler diagram is valid for steels containing 0.1% or less carbon. When the carbon concentration is much more than this value, the effect of carbon is significantly lower.

The sharply decreasing austenitizing effect of carbon is well documented and that is why the microstructure of welds contains much more martensite than is predicted by the Schaeffler diagram.

Welds with such composition can be produced when unalloyed, and low- or medium-alloy steels are welded with austenitic Cr-Ni filler material. Due to the dilution, the Cr in weld metal ranges between 12 and 14%, the Ni might decrease to as low as 5 to 7%, while the C content rises up to 0.2%, and sometimes to 0.3%. Because of this, a question has arisen as to how much the coefficient of the carbon is in the calculation formula for the Ni equivalent.

KEY WORDS

Austenitizing Effect
Nickel Equivalent (Ni_{eq})
Modified Nickel Equivalent (Ni_{eqB})
Schaeffler Diagram
M_s Temperature
Creep Resistant Steels
Crack Sensitivity
Welding Dissimilar Metals

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Analysis of the Schaeffler Diagram

According to the general conception, the original Schaeffler diagram illustrates the common effect of the austenite and ferrite forming elements. On the basis of this fact, it can be stated with confidence that a steel with 12% Cr equivalent and 9.5% Ni equivalent falls into the martensitic area, but with extra alloying of 6% Ni, it becomes fully austenitic (Ref. 5). This might be considered the common effect of the austenitizer elements. On the other hand, an interesting case occurs when a steel with 12% Ni_{eq} and 9% Cr_{eq} has a martensitic structure, but after the addition of 7.5% Cr, the microstructure becomes austenitic, in spite of the fact that the Cr is a ferritizing element. It means that the Schaeffler diagram does not reflect the collective effect of the austenite and ferrite forming elements, but shows another influence, which is common for both groups of alloying elements and is directed to the austenite forming process. There is only one phe-

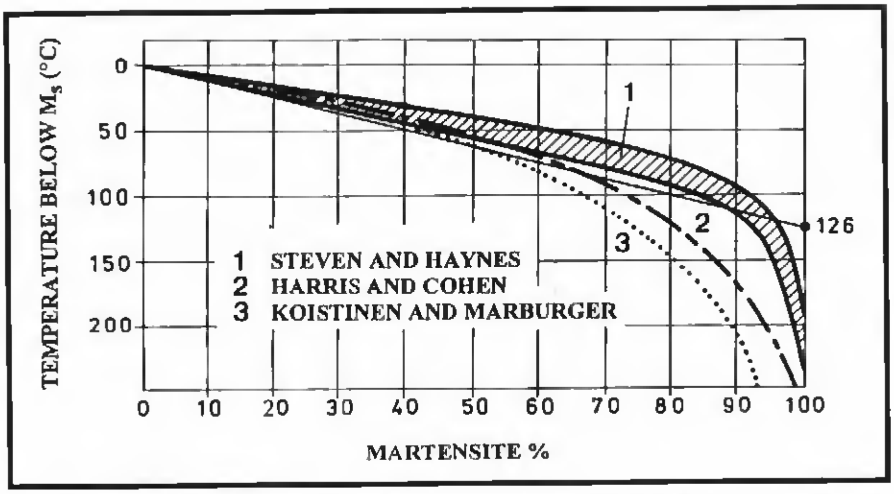

Fig. 1— Percentage of martensite in steels with different compositions, at temperatures below M_s: 1) C = 0.32 to 0.44%; 2) NiCrMo alloyed steels with C content of 0.32 to 0.48%; 3) Steels with C content of 1.1%.

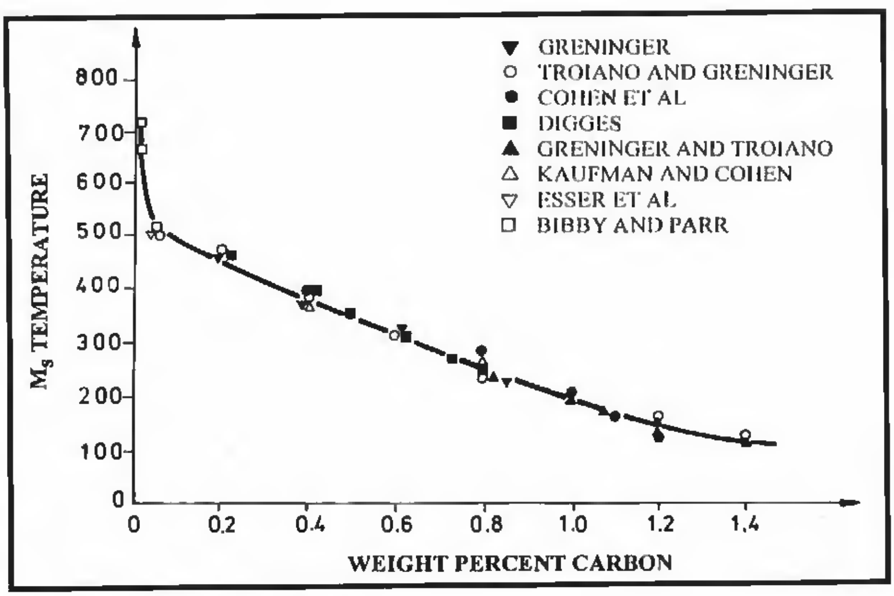

Fig. 2 — M_s temperature of unalloyed steels.

nomenon that explains this observation: all alloying elements decrease the M_s temperature.

According to Fig. 1 (Ref. 6), below the M_s temperature, the martensite in the microstructure proportionally increases with temperature in such a way that at M_s-126°C the microstructure was fully austenite. The aforementioned addition of 6% Ni or 7.5% Cr can be evaluated as an action that decreases the M_s temperature by 126°C. It follows from this that 1% of Ni decreases the M_s temperature by 126/6 = 21°C and 1% of Cr by 126/7.5 = 16.8°C. This means that a 1% increase in Ni content can increase the austenite by 100/6 = 17%.

Of course in the previous sequence of ideas, Ni can be substituted by Ni equivalent (without carbon) and Cr by Cr equivalent.

Effect of Alloying Elements

The previously mentioned elements decrease the M_s temperature, therefore, the unalloyed carbon steels have the highest M_s temperature. Denote this temperature by M_{sC}. According to Fig. 2 (Ref. 6), with up to approximately 0.07% of C content, a small change in C causes a big drop in the M_{sC} temperature, while with more than 0.1% of carbon content, the change becomes moderate.

The strength of the austenitizing effect of any alloying element can be measured with the decrease in M_{sC} temperature caused by a 1% increase in concentration of the given element. For low-carbon steels, this effect is much stronger than 30 times the effect of Ni, and, in accordance with the investigation of Ornig (Ref. 7), at 0.2% C concentration, this effect is only 15 times that of nickel.

On the basis of the published data found in Fig. 2, regression equations were calculated; therefore, the M_{sC} temperature (in °C) of unalloyed steels can be approached as follows:

$$0.03 \le C < 0.35 \quad M_{sC} = 454 - 210\cdot C + \frac{4.2}{C} \tag{1}$$

$$0.35 \le C < 1.3 \quad M_{sC} = 332 - 190\cdot C + \frac{40}{C} \tag{2}$$

$$1.3 \le C < 2.2 \quad M_{sC} = 116. \tag{3}$$

The alloying elements of steels further decrease the M_{sC} temperature. According to Fig. 1, the M_s temperature of the alloyed steels can be written as the function of the most important elements:

$$M_s = M_{sC} - 21\cdot(Ni + 0.5\cdot Mn) - 16.8\cdot(Cr + Mo + 1.5\cdot Si). \tag{4}$$

Let us consider this relationship as a multivariable function. The change of M_s temperature due to the change of independent variables can be obtained by partial differentiating of Equation 4:

$$dM_s = \frac{\partial M_s}{\partial C}\cdot dC + \frac{\partial M_s}{\partial Ni}\cdot dNi + \ldots + \frac{\partial M_s}{\partial Si}\cdot dSi. \tag{5}$$

Completing the marked operation

$$dM_s = -21\left[\left(10 + \frac{0.2}{C^2}\right)dC + dNi + 0.5\cdot dMn\right] - 16.8\cdot(dCr + dMo + 1.5\cdot dSi). \tag{6}$$

The M_s temperature's decreasing effect on the ferritizing element is linear, therefore, their simultaneous effect on the nondifferential changes (let us call it traditionally equivalent) is as follows:

$$Cr_{eq} = Cr + Mo + 1.5\cdot Si. \tag{7}$$

The effects of Ni and Mn on M_s temperature are also linear, and the change in carbon compared to the other elements is small, so the simultaneous effect of the austenitizer element on the nondifferential changes can be expressed as

$$Ni_{eqB} = Ni + 0.5\cdot Mn + 10\cdot C + \frac{0.2}{C}. \tag{8}$$

Let us consider steel as austenitic if its M_s temperature falls below 0°C. The carbon content of austenitic stainless steels varies according to Equation 1. Selecting a steel with optional C content and a nickel equivalent between 10 and 18% and taking this condition into account, the (Ni + 0.5·Mn) sum can be expressed from Equation 4. The point belonging to the Ni_{eqB} and Cr_{eq} coordinates is located on the straight line bordering the austenite area. For a given carbon content, this point is on the line that is parallel to the borderline of the austenite area in the Schaeffler diagram. Since $Ni_{eq} = Ni_{eqB}$ at 0.1% of carbon content, the effect of carbon compared to that of Ni is 30 times greater, as shown in Fig. 3 (Ref. 8).

In the modified diagram, two different nickel equivalents can be found. For microstructure prediction of stainless steel base and weld metal with Cr_{eq} >18%, the Schaeffler's nickel equivalent (Ni_{eq}) can be used, but below 18% chromium equivalent, the new nickel equivalent (Ni_{eqB}) should be applied. It follows from this that during welding on unalloyed steel, the microstructure of the weld cannot be predicted by the usual constructional method because the position of the unalloyed welds cannot be pointed out. In these cases, the chemical composition of the weld should be determined by calculation, taking the dilution into account.

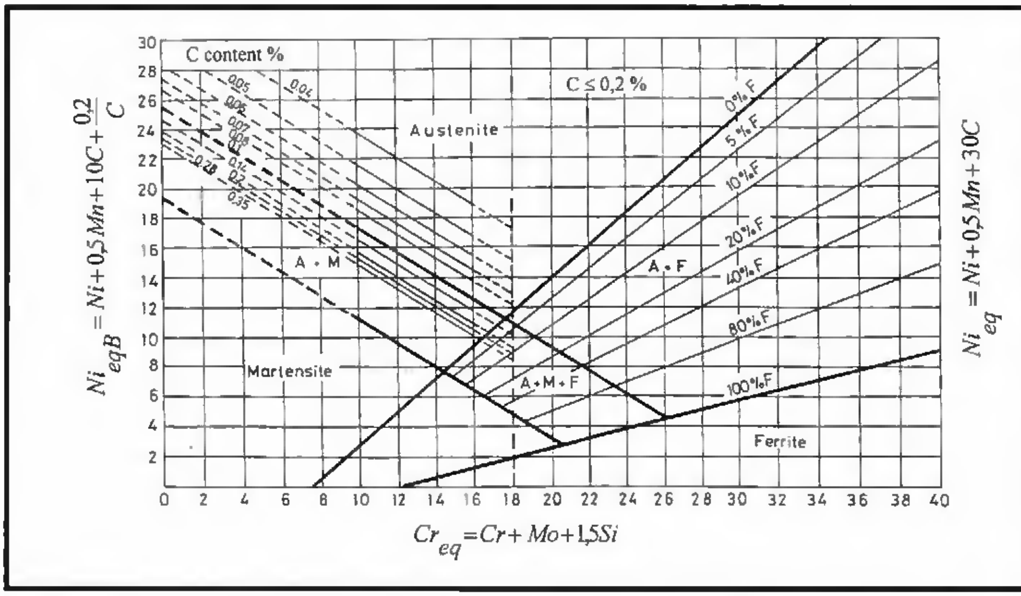

Fig. 3 — Modified Schaeffler diagram taking into consideration the effect of change in C content.

The microstructure of a steel or a weld metal with a given C concentration will be austenitic only when its composition point is located above the straight line of that C content.

According to works of Gow and Harder (Ref. 9) and Nekhendzy (Ref. 10), in the steels having less than 10% Cr, the austenitizing effects of Ni and Mn, compared to each other, change strongly, and in steels containing more than 1.75% of Mn and approximately 1% Cr, a 1% extra Ni addition decreases M_s temperature half as much as does manganese.

The previous statement means that below a 10% Cr equivalent, the Schaeffler diagram distorts increasingly. It follows from this that the unalloyed steels cannot be part of the diagram. With regard to the linearity and the fact that during welding unalloyed steel with Cr-Ni filler metal the Cr equivalent in the weld metal is more than 10%, the Schaeffler diagram can be satisfactorily used under 0.1% carbon content for determination of weld microstructure. When the carbon content is different from 0.1%, the diagram can underestimate the martensite ratio by as much as 15%. That is why using the modified Schaeffler diagram is suggested.

Generalization of Equation 4

By reevaluating the results of Eichelmann and Hull (Ref. 11), it can be concluded that an increased concentration of alloying elements strengthens the austenitizing effect. Besides, it is well known that in the Fe-Ni alloys with less than 5% Ni, the $\gamma \rightarrow \alpha$ transformation temperature decreases with increasing Ni content, more so than for the same alloys having more than 5% Ni. On this basis, the generalization of Equation 4 becomes practical by the use iteration method. In Refs. 12–14, exact compositions and measured M_s temperatures of more than 300 steels are given. Using this data base, a new relationship was established between the M_s temperature and the chemical composition of steel.

A regression relationship between the chemical composition of steels and their measured M_s temperature was established. The generalized form of the suggested equation that is valid for all types of steels except for microalloyed ones is as follows:

$$M_s = M_{sC} - x \cdot Ni - y \cdot Mn - z \cdot Cr_{eq} - 21 \cdot Cu. \quad (9)$$

The values of the regression coefficients x, y and z are summarized in Table 1. These coefficients can be considered theoretically dependent on the concentration of alloying elements, but a more exact determination is not possible yet since industry produces only steel grades demanded by users. It is understandable that data for steels of different Cr + Si concentrations have been missing up to now.

It was found from the original data in the literature that cobalt content as high as 6 to 8% does not affect the M_s temperature of high-speed steels; therefore, it is not included in Equation 9. The coefficient of Cu is constant.

Coefficients given in Table 1 are valid for composition limits of steels used in industry. Specifying the application for the steels makes selection of coefficients easier.

Since knowledge of the M_s temperature is very important for both the specialists of heat treating and welding, many researchers tried to determine an empirical relationship for calculating the M_s temperature (Refs. 15–17). Analyzing these functions, it was found that the M_s equations are valid only in narrow concentration intervals, and outside these ranges the calculated temperatures might deviate from the measured ones by as much as 100°C (Ref. 18). The suggested formula is much more accurate, and it is valid within a broad composition range. The regression coefficient computed from data of more than 300 steel grades was 0.989. This accuracy is sufficient to use the calculated M_s temperature for determining preheating temperature when the welding procedure is detailed.

It follows from this that the M_s temperature can be calculated with some degree deviation, and the suggested modification of the Schaeffler diagram is acceptable.

As an example of proof, the welding of P91 and T91 (ASTM A213, ASTM A335) creep-resistant steels is given. For these steels, the measured M_s temperature differs from the calculated one by no more than a few degrees (Ref. 19).

From experience it has been noted

Table 1 — Determination M_s Temperature of Different Steels

$$M_s = M_{sC} - x \cdot Ni - y \cdot Mn - z \cdot Cr_e - 21 \cdot Cu, \ ^\circ C$$

Conditions		Coefficients				Applications
C, Cr, Si	Ni	x	y		z	Typical welds and base metals
	>5	21	10.5		16.8	Pearlitic-martensitic stainless steels (Cr_{eq} <18%); soft martensitic CrNi steels; welds in heterogeneous joints; austenitic buffer layers on mild and quenchable steels
$0.03 \leq C < 0.5$ and	1.4 to 5	$\left(1.6Ni + \frac{65}{Ni}\right)$	10.5		16.8	
$(Cr + 1.5Si) > 6$	<1.4	27	7.8		9.5	High-alloyed creep-resistant steels; hot working die steels, with CrMoSi or CrWSi alloying
$0.03 \leq C < 2.3$ and			$Mn \geq 1.75$	$Mn < 1.75$		
$(Cr + 1.5Si) \leq 6$ or	>5	15.6	31.2	7.8	2.1	Unalloyed, low- and medium-alloyed steels; high-speed steels; Ledeburitic
$0.5 \leq C < 23$ and	2 to 5	$\left(1.2Ni + \frac{48.7}{Ni}\right)$	31.2	7.8	2.1	Cr steels; alloyed steels with high Ni
$(Cr + 1.5Si) > 6$	<2	27	31.2	7.8	2.1	or Mn content; Hadfield steels

that the crack susceptibility of high-alloy creep resistant steels changes when another heat of steel is welded. According to the calculations made with the proposed equation for a given steel, a difference of 80°C in M_s temperature for steels selected from different heats might be possible. Applying the same preheating temperature, the crack susceptibility will be very different, because up to a 60% difference can occur in martensite content in the weld metal — Fig. 1.

Possibly the least crack susceptibility might be achieved if the martensite in the weld metal is uniformly about 50%. A possible explanation for this is that during $\gamma \rightarrow \alpha$ transformation the volume is changed and inner stress forms (Ref. 20). As shown by Fig. 1, during welding the interpass temperature should he kept below the M_s temperature by 50° to 70°C.

The suggested formula offers important information for the welding of homogeneous or heterogeneous joints of creep-resistant steels (Ref. 21), and it makes determining the change of microstructure in the carbide-rich zone possible (Ref. 22).

Conclusions

When ferritic-pearlitic steels are welded with austenitic Cr-Ni filler metal, much more martensite is frequently formed in the weld metal than could be predicted by the Schaeffler diagram. This observation can be explained by the fact that the diagram does not take into consideration the strong affect of varying carbon. From this investigation, an improvement in the Schaeffler diagram for the section under 18% of chromium-equivalent is suggested. A generalized mathematical formula was derived by which the M_s temperature of any widely used steel grade can be calculated with sufficient accuracy for practical use.

This offers welding engineers a new point of view. Moreover, it creates the right conditions for determining preheating temperature on the basis of the chemical composition of a given steel heat when the welding procedure is detailed.

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