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Welding of Martensitic Creep-Resistant Steels

The relationship between preheat and M_s temperatures was investigated

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ABSTRACT. The majority of equipment and pipelines working at high temperatures in fossil-fueled power stations are made of creep-resistant steel with 9 to 12% chromium. For joining this type of steel, martensitic welding is undertaken, which is carried out following preheating to a temperature lower than the M_s. The preheat temperature is usually determined by experiments or following normal industrial practice. In spite of this, some materials are markedly crack sensitive, and moreover, cracks form in the welded joints. The authors have carried out detailed investigations to explore the reason for this phenomenon and have constructed a method to reduce such failures. The principal goal of this research was to provide a solution for welding of high-chromium, martensitic, creep-resistant steel with repeatable high quality.

Introduction

The characteristic types of martensitic creep-resistant steels are 0.2C 12Cr 1Mo and the recently developed 0.1C 9Cr 1Mo. The conventional continuous cooling transformation (CCT) diagrams belonging to a given chemical composition are presented in Figs. 1 and 2 (Refs. 1, 2). Notably, there is an 80°C difference in the M_s temperature of the two steel grades. The difference is due to the lower carbon (0.1%) and lower chromium (3%) content of the 9Cr steel, since the other alloying elements are the same. This observation confirms the common knowledge that the composition of the steel affects the M_s temperature.

Welding practice, temperature measurements and calculations equally show that in spite of the widely used preheat temperature of 300°C and a correspondingly high heat input, the metal austenitized during welding cools to 500°C within 100 to 150 seconds and, as a result, the cooling curves are far removed from the austenite transformation curves. This suggests that the previously austenitized volume reaches the M_s temperature in a fully austenitic condition, and subsequently cools further to the preheat temperature with some part of the austenite therefore transforming into martensite. At low temperature (below M_f), following the welding operation, the retained austenite transforms into martensite independently of the preheat temperature and the duration of welding.

In the weld metal and part of the heat-affected zone (HAZ), where the $\alpha \rightarrow \gamma \rightarrow \alpha$ transformation occurred, the proportion of martensite is always considerable; therefore, during welding, a certain risk of cracking may need to be considered. As a consequence of these arguments, welding engineers may need to have a general knowledge of the most important microstructural transformations and the related changes in strength (Ref. 3).

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KEY WORDS

Martensitic Steel
Chrome-Moly
Weld Cracking
Creep Resistant
High Temperature
Power Plants

Characteristic Changes in the Microstructure of Creep-Resistant Steels

The quantity of martensite transformed from austenite depends on the temperature undercooling below the M_s (Ref. 4). This transformation is almost independent of the composition, and takes place in all steel grades as shown in Fig. 3.

Initially, this relationship has a linear characteristic, and it is suggested this may be estimated by a straight line by which the transformation is completed at M_s – 126°C. Where the volume fraction of martensite is above 90%, the transformation slows down and finishes at approximately $M_f = (M_s - 190) \pm 10°C$.

Ornig (Ref. 5) considered the section of the Schaeffler diagram under 18% chrome-equivalent was not accurate. Considering the detail in Fig. 3, it is possible to derive a regression equation suitable for estimation of the M_s temperature for any steel grade with very good fit (Refs. 6, 7). This was made possible by the authors' research, which is the subject of this paper. The basis of our analysis is supported by the latest results of Ref. 8.

The suggested equation for the M_s temperature of martensitic creep-resistant steels is as follows (concentrations are in wt-%):

$$\begin{aligned} M_s = {} & 454 - 210 \cdot C + \frac{4.2}{C} \\ & -27 \cdot Ni - 7.8 \cdot Mn \\ & -9.5 \cdot (Cr + Mo + V + W + 1.5 \cdot Si) \\ & -21 \cdot Cu \end{aligned} \qquad (1)$$

The good fit for this equation is characterized by the fact the difference between the calculated and the measured temperatures is only a few degrees and the correlation coefficient is very close to 1 (0.9898).

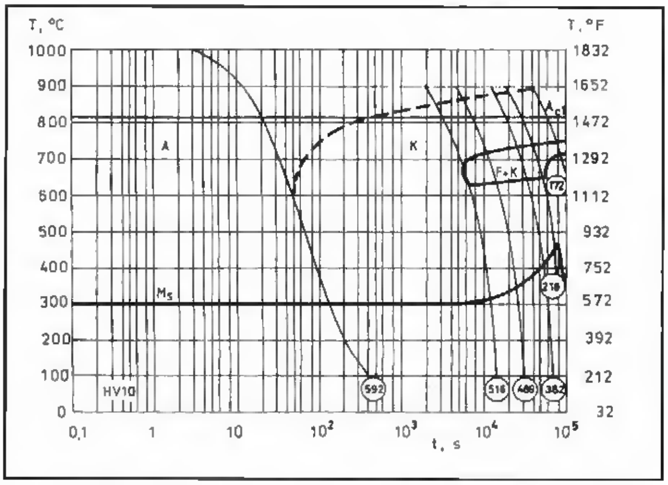

Fig. 1 — The conventional CCT diagram of the 0.2C-12Cr-1Mo steel (Ref. 1). The composition of the heat: C = 0.21%, Si = 0.34%, Mn = 0.86%, Cr = 11.28%, Ni = 0.31%, Mo 0.50%, V = 0.29%; austenitization: 1050°C, 10 min., A_{c1} = 820°C, M_s = 300°C.

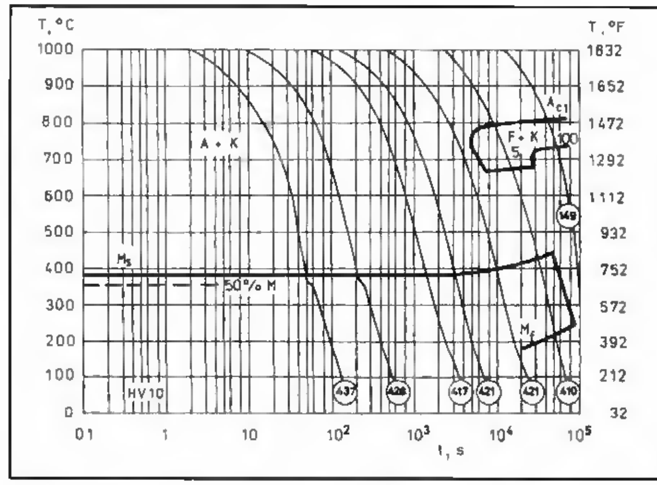

Fig. 2 — The conventional CCT diagram of the 0.1C-9Cr-1Mo steel (Ref. 1). The composition of the heat: C = 0.10%, Si = 0.34%, Mn = 0.42%, Cr = 8.75%, Ni = 0.13%, Mo = 0.96%, V = 0.20%; austenitization: 1040°C, 10 min, A_{c1} = 810°C, M_s = 380°C.

Equation 1 is suitable even for calculation of the M_s temperature of creep-resistant steels and gives very satisfactory results. Rows 1, 2 and 3 of Table 1 contain the measured temperatures. The calculated values differ from these by only a few degrees.

In rows 4 and 5 of Table 1, the chemical compositions of the two samples are different, but these are frequently used types of creep-resistant steel. It is suggested careful attention be given to the 60 to 70°C difference in the M_s temperatures, which form the upper and lower content limits in international standards. As a consequence, if the preheat temperature is chosen independently from the composition of the steel heat, in the case of welding steels at the composition limits, there may be a 50–60% difference in martensite content. Consequently, the steel with the higher martensite quantity may crack.

The new theory for determination of preheat temperature is suitable for separating the bainitic-martensitic creep-resistant steels containing less than 5% of chrome from the martensitic steels with more than 5% of chrome, and it is possible to suggest reclassification of steels in the standard EN 288-3 (Ref. 9).

According to Fig. 3, when welding is carried out at the preheat temperature M_s–25°C, approximately 20% of martensite can be found in the microstructure of previously austenitized steel, but at M_s–75°C, the proportion of martensite reaches 60%. This may mean a 50°C difference in preheat temperature increases the martensite concentration up to three times.

Martensitic creep-resistant steels contain such high levels of alloying elements that, above the M_s temperature, the nonmartensitic transformation of austenite will not commence for a considerable time (even for weeks in some cases) (Ref. 1).

If the welding temperature above the M_s temperature is chosen, the previously austenitized volumes of the joint remain in austenitic (*i.e.*, ductile) condition until the welding operation is completed. This is the principal idea of austenitic welding. There is no crack susceptibility until welding ceases, but considerable austenite transforms into martensite during cooling. This process causes a significant increase in specific volume. As a consequence, high (tensile) residual stress can result in cracking.

When martensitic welding is carried out, some martensite has already formed during welding. For a correctly selected welding (preheat) temperature, there is a considerable amount of ductile austenite, which is why the crack susceptibility is quite low. Moreover, the martensite formed earlier is tempered during welding of subsequent passes. Another favorable effect is that only a little austenite will transform into martensite during cooling. Thus, the advantages of martensitic welding, on the one hand, give lower stress levels, which tends to reduce crack susceptibility; on the other hand, lower preheat temperatures result in energy savings. Due to its considerable advantages in practice, martensitic welding is commonly preferred to austenitic welding.

Table 1 — Composition and M_s Temperature of Creep-Resistant Steels

List Number	Type of Steel	Typical Chemical Composition in wt-% C	Si	Mn	Cr	Mo	Ni	V	Others	M_s Temperature, °C Calculated	Measured
1	0.2C 12Cr 1Mo	0.21	0.34	0.50	11.28	0.86	0.31	0.29	—	293	300
2	0.2C 12Cr 1Mo W	0.22	0.35	0.52	12.00	1.35	0.59	0.31	W = 0.40	268	267
3	0.1C 9Cr 1Mo V	0.10	0.36	0.42	8.75	0.96	0.13	0.20	Nb = 0.07	368	380
4	0.2C 12Cr 1Mo	0.17	0.20	0.40	10.00	0.80	0.30	0.25	—	324	
		0.23	0.50	1.00	12.50	1.20	0.80	0.35		254	
5	0.1C 9Cr 1Mo	0.08	0.20	0.30	8.00	0.85	0.20	0.18	Nb = 0.06	393	
		0.12	0.50	0.60	9.50	1.05	0.40	0.25	Nb = 0.10	339	
6	0.2C 12Cr 1Mo	0.19	0.35	0.48	10.40	0.89	0.71	0.26	—	298	
7	0.1C 9Cr 1Mo	0.10	0.31	0.47	8.52	0.93	0.28	0.20	Nb = 0.07	367	

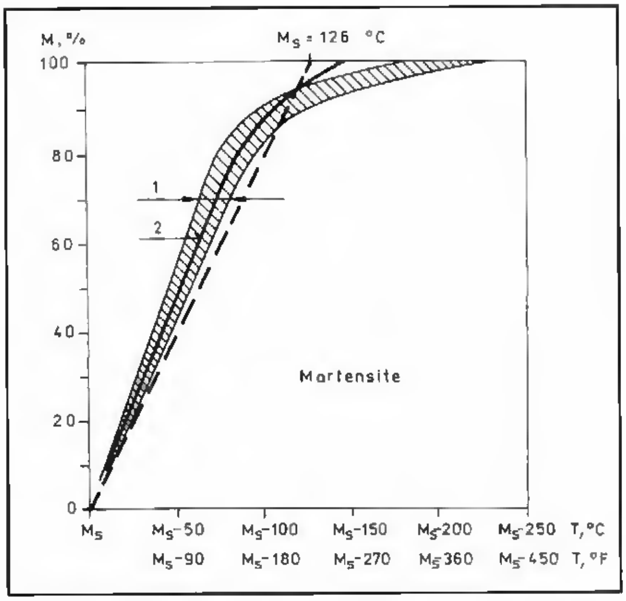

Fig. 3 — The fraction of martensite in the microstructure against the temperature below M_s (Ref. 4). 1 — Steven and Haynes (Carbon steel, C = 0.35%); 2 — Kauhausen (alloy steel, 0.2C 12Cr 1Mo).

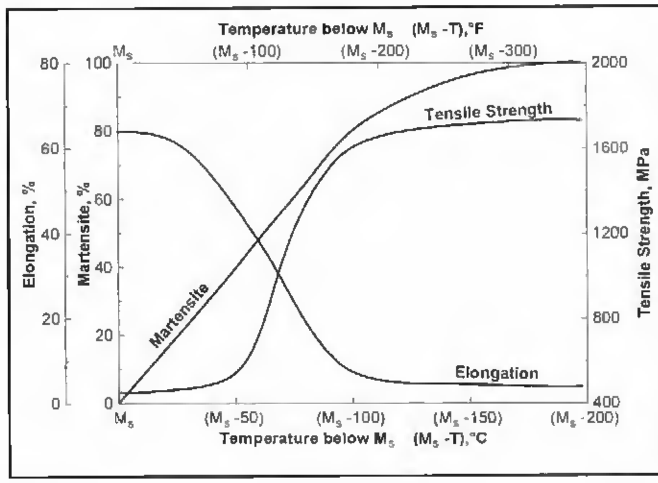

Fig. 4 — Martensite fraction, elongation, and tensile stregth of a 0.2C-12Cr-1Mo-type creep-resistant steel cooled from the austenitizing temperature to the testing temperature.

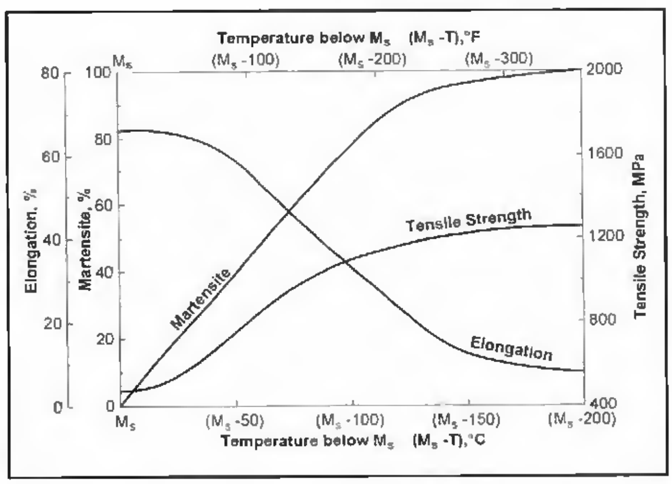

Fig. 5 — Martensite fraction, elongation and tensile stregth of a 0.1C-9Cr-1Mo-type creep-resistant steel cooled from the austenitizing temperature to the testing temperature.

Properties of Previously Austenitized Steels Cooled to Preheat Temperature

On the basis of the previous paragraph, it may be concluded that neither a high preheat temperature is favorable (because of the crack sensitivity during cooling), nor one that is too low (because of the risk of cracking during welding due to excessive martensite formation).

Investigations were conducted to determine the minimum temperature necessary, *i.e.*, the optimum preheat temperature. For this purpose, tensile specimens previously austenitized then cooled to the testing temperature were examined. In the tested condition, the microstructure was found to be the same as in the HAZ of the welded joint after $\alpha \rightarrow \gamma \rightarrow \alpha$ transformation occurred due to the welding heat cycle.

In the course of research on the 0.2C-12Cr-1Mo and 0.1C-9Cr-1Mo type steels, the chemical compositions given in rows 6 and 7 of Table 1 were used. Five-mm-diameter, cylindrical specimens were austenitized at 1050°C for 10 min. Then the specimens were cooled to the tensile testing temperature within 30 seconds and placed in the furnace of a computer-controlled, MTS-type testing machine, where they were test loaded in the warm condition by a tensile force until fracture. Considering the CCT diagrams of these steel heats presented in Figs. 1 and 2, the reader may observe this rapid cooling guarantees a fully austenitic microstructure when the temperature decreases to the M_s temperature and the austenitic-martensitic condition at the testing temperature.

The results of these tensile tests are given in Table 2. It can be seen from this data that the specific elongation of both steel heats decreases sharply while their strength increases markedly. These phenomena are the result of the increasing martensite content, the quantity of which can be estimated using Fig. 3, after calculation of the M_s temperature by Equation 1.

According to the data in Table 2, the elongation only decreases significantly below the M_s temperature (Ref. 10). Above the M_s temperature, it appears to be relatively constant.

The temperature at which the steel is tough enough to suffer the strain originated from welding can be selected only with mutual consideration of ultimate tensile strength, specific elongation and martensite content. To assist understanding of this concept, the three curves in the function of the temperature below the M_s are illustrated in one graph.

Figure 4 illustrates the properties of the steel whose composition is given in row 6 of Table 1. Since the composition of the 0.2C-12Cr-1Mo-type creep-resistant steel varies across a broad range, the M_s temperature changes between 254 and 324°C, depending on the composition. Figure 4 seems to be suitable to characterize all the steel heats within the standard interval, particularly because the composition of the experimental heat is close to the mean of the standard range.

In case of steels with 0.2% C, there is a generally accepted welding rule for avoiding crack formation that the maximum tensile strength in the joint should not exceed 1000 MPa (approximately 300–350 HV). Figure 4, illustrating the properties of the steel valid for conditions of welding, assists in selecting the correct preheat temperature. To keep tensile strength below 1000 MPa, the preheat temperature must be high enough such that a minimum 30 to 35% of martensite should be formed. On the basis of this

Table 2 — Martensite Content and the Results of Tensile Test of the Previously Austenitized Creep-Resistant Steels Cooled to the Different Testing Temperatures within 30 s

	Type of Steel							
	0.2C 12Cr 1Mo (M_s = 298°C)				0.1C 9Cr 1Mo (M_s = 367°C)			
Temperature of Tensile Test °C	T_p, °C	E, %	TS, MPa	M, %	T_p, °C	E, %	TS, MPa	M,%
400	M_s+102	61	390	0	M_s+33	66	470	0
350	M_s+52	62	400	0	M_s–17	66	500	14
325	M_s+ 27	63	428	0	M_s– 42	62	675	33
300	M_s+2	64	450	0	M_s–67	50	900	53
275	M_s–23	62	460	18	M_s–92	37	1060	72
250	M_s–48	48	525	38	M_s–117	25	1150	88
230	M_s–68	31	995	55	M_s–137	16	1200	94
225	M_s–73	21	1290	63	M_s–142	13	1215	96
200	M_s–98	8	1590	79	M_s–167	10	1240	98
150	M_s–148	5	1710	96	M_s–217	8	1250	100
100	M_s–198	4	1730	100	M_s–267	8	1260	100
20	M_s–278	4	1725	100	M_s–347	8	1280	100

Abbreviations: T_p preheating temperature
E elongation in 25 mm
TS tensile strength
M martensite

consideration, the recommended preheat temperature is as follows:

$$T_p\ 12Cr = (M_s - 60) \pm 10°C \qquad (2)$$

The conventional CCT diagrams show the change of cooling rate in practice does not affect the hardness of the steel. In accordance with Fig. 3, the hardness during welding depends only on the preheat temperature, since the martensite content is controlled by the preheat.

The upper limit of the suggested interval should be used for thicker pipe walls since, in the case of 30 to 40 mm thicknesses, the temperature at the inner surface (the location of the root pass) is 15 to 20°C lower than at the outer surface where the temperature sensor is located. In contrast, during welding of thin-wall pipes, the metal may be overheated due to the moderate heat conduction. It is therefore advised to prescribe the lower limit of the preheat interval, combined with short breaks to avoid overheating.

After welding, the joint should be cooled to the temperature, or some degrees below, at which the austenite can fully transform into martensite before commencement of the tempering operation. Corresponding with Ref. 4, the highest recommended value, the so-called intermediate temperature (T_i) can be calculated as follows:

$$T_i = (M_s - 190) \pm 10°C \qquad (3)$$

This temperature is suitable because, in accordance with Kauhausen's measured data (Ref. 1), transformation of austenite into martensite is almost fully complete at the temperature M_s – 150°C to M_s – 160°C. For this steel type, further cooling is unnecessary and, therefore, following 1 to 2 h holding time at temperature T_i, the tempering step should be started immediately.

However, in the standard composition interval of the 0.2C-12Cr-1Mo-type steel, the C content can vary by 0.06% and the Cr by 2.5%; therefore, the difference in the M_s temperature between the steel heats belonging to the upper and lower composition limits can reach 70°C. It can be seen from Fig. 3 that a 70°C change in temperature causes a 60% difference in martensite content. This deviation is almost so much it is between the medium compositions of the 0.2C-12Cr-1Mo- and the 0.1C-9Cr-1Mo-type creep-resistant steels. It follows from the aforementioned that the crack susceptibility of the base metals rolled from different heats can be very different, particularly if the preheat temperature was independently prescribed from the heat composition (Ref. 11).

Welding practice in the last 40 years used very different, empirical preheat temperatures, since the theoretical relation between weldability and preheat temperature had not been considered. The manufacturers of the base and filler metals have previously advised 200 to 300°C preheat and interpass temperatures.

Since the composition of the base metals might change over a wide range, the randomly chosen preheat temperature for all steels cannot be optimum. Since the composition of the steel heats are always available where a quality assurance system is operated, welding experts can calculate the M_s temperature before elaborating the required procedure qualification records (PQR).

The values of this broad interval do not always give the expected crack-free result. Consider the following examples to explain what problems can occur if the preheat is chosen without taking the real heat composition into account. When a steel of the lower composition limit (M_s = 324°C) is welded at a preheat temperature of 200°C, welding is carried out at M_s – 124°C . It can be seen in Fig. 4 the characteristic properties of the previously austenitized steel volumes are tensile strength = 1680 MPa, elongation in 50 mm = 5% and martensite fraction = 90%. Hardness can attain the 550 HV value and the joint might crack during welding.

When a steel of the upper composition limit (M_s = 254°C) is welded at a preheat temperature of 300°C, welding is carried out at M_s + 46°C, which is austenitic welding. In this case, cracks can form during cooling to the interpass or room temperature.

The situation is similar when the 0.1C-9Cr-1Mo-type steel is welded — Fig. 5. In accordance with the measuring of the Mannesmann Research Institute, Germany (Ref. 12), the hardness in the quenched condition ranges from 380 to 440 HV_{10}. Due to the lower C content and the higher elongation, a higher martensite ratio can be allowed in the microstructure while maintaining the same crack risk with decreased preheat temperature.

$$T_{p9Cr} = (M_s - 90) \pm 10°C \qquad (4)$$

The intermediate temperature (T_i) may be the same as advised for the 0.2C-12Cr-1Mo type:

$$T_i = (M_s - 190) \pm 10°C \qquad (5)$$

Since the C content is low, the welded joint is permitted to cool to room temperature and can be held for a long time, but their martensitic microstructure (*i.e.*, brittle, impact sensitive) should be taken into account when the joints are handled.

The crack sensitivity of the newly developed 0.1C-9Cr-1Mo-type steels is lower than the 0.2C-12Cr-1Mo type, but the proper determination of the preheat and interpass temperatures for these is also important. At the lowest possible preheat temperature (M_s – 100°C), the steel contains 80% martensite, tensile strength is 1100 MPa and the elongation is already above 30% — Fig. 5. To avoid problems, the crack susceptibility of these steels should be considered.

Conclusions

According to the research detailed in this paper and supporting industrial experience, it is recommended to calculate the preheat temperature only with full knowledge of the chemical composition of the steel heat in order to attain the optimum strength parameters of the joint.

A regression analysis of the transformation data from more than 350 martensitic steels was used to relate the M_s to the chemical composition and is of the following form:

$$M_s = 454 - 210 \cdot C + 4.2/C - 27 \cdot Ni - 7.8 \cdot Mn - 9.5 \cdot (Cr + Mo + V + W + 1.5 \cdot Si) - 21 \cdot Cu.$$

Using this relationship, it was shown the M_s temperature could vary by up to 70°C due to compositional variations within the specification for the steel compositions.

Tensile testing showed that for partially transformed specimens, elongation decreased and tensile strength increased as the fraction of martensite in the microstructure increased.

The combination of austenite transformation data, embodied in the expression for M_s, and the tensile test data was used to determine the optimum conditions for welding preheat.

Knowledge of the martensite content and the mechanical properties seems to be very useful in cases when, due to the local conditions, geometry, dimensions or other reasons, the optimum preheat temperature may not be maintained. Diagrams help to weigh the problems that might occur during welding.

Determination of the optimum preheat temperature for martensitic creep resistant steels, and, indeed, all martensitic steels, is important. When a martensitic steel is to be welded, and the steel heat contains higher levels of alloying elements, the preheat temperature should be decreased to keep the ratio of austenite to martensite and the crack sensitivity ratio to a low level.

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