Theoretical calculation of the finishing rolling elongation in alloying non-quenched and tempered steel*

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Abstract The finishing rolling elongation δ of the alloying non-quenched and tempered steel is calculated with the covalent electron number n_A of the strongest bond of the alloying phases and the interface electron density difference $\Delta\rho$ of the phase interfaces. The calculations show that the elongation $\delta^{\alpha\text{-Fe}}$ of the matrix α-Fe decreases with rolling refinement, the elongation $\delta^{\alpha\text{-Fe-C-}M}$ of solid solution phases (M denotes alloying element) is inversely proportional to the covalent electron number $n_A^{\alpha\text{-Fe-C-}M}$ of the strongest bond, the elongation decrement $\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M}$ caused by interface strengthening is directly proportional to the interface electron density difference $\Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M}$, but the elongation decrements $\Delta\delta^{\alpha\text{-Fe}/M_CC_1}$ and $\Delta\delta^{\alpha\text{-Fe-C}/M_CC_2}$ caused by dispersion strengthening and precipitation strengthening respectively are directly proportional to the ratio of the electron density difference $\Delta\rho^{\alpha\text{-Fe}/M_CC_1}$ and $\Delta\rho^{\alpha\text{-Fe-C}/M_CC_2}$ of the strengthening interfaces to $\Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}$ of the basic interface α-Fe/α-Fe-C. Therefore, the finishing rolling elongation of the alloying non-quenched and tempered steel is considered to be subtracting all the elongation decrements of solution strengthening, interface strengthening, dispersion strengthening and precipitation strengthening from the elongation of the refined α-Fe matrix. The calculation formulas in this paper are integrated with the proposed ones of σ_S, σ_b and of α_K delivered in another paper, the finishing rolling mechanical properties can be achieved and the calculated results agree well with the measured ones.

Keywords: electron structure parameters, alloying non-quenched and tempered steel, elongation, theoretical calculation.

Based on the chemical compositions of alloys and prepared technologies, the alloying mechanical properties can be forecast and calculated, which is the key content of alloying composition theory design. Since the middle of the 20th century, many workers of material science have fruitfully established commercial software of knowledge base, data base, expert system and regressive technique through different research methods on different levels. Recently, the analogy calculations have also appeared based on the neurotic network. However, based on hot-continuous rolling technology, Liu et al.[1—5] have attempted to theoretically calculate and predict the finishing rolling mechanical properties of the alloying non-quenched and tempered steel with the alloying electron structure parameters.

Liu et al.[5] have calculated the finishing rolling elongation of the non-quenched and tempered Si-Mn steel with the covalent electron number n_A of the strongest bond of alloying phases and the interface electron density difference $\Delta\rho$. In the calculation, we found that the finishing rolling elongation of the non-quenched and tempered Si-Mn steel is subtracting all the elongation decrements of solution strengthening, interface strengthening and precipitation strengthening from the refined α-Fe matrix. Based on the calculations of Ref. [5], calculations of the finishing rolling elongation of the alloying non-quenched and tempered steel with the common elements of Cr, Ni, W, Mo and Cu (denoted by M) and the microelements of V, Nb and Ti (denoted by M_C) are continuously studied in this paper, and the general calculation formulas of elongation δ are proposed by integrating with the calculations of σ_b, σ_s in Refs. [1—4] and of α_K delivered in another paper.

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1 Phases, phase interfaces and their electron structure parameters of the alloying non-quenched and tempered steel after finishing rolling

1.1 Phases and phase interfaces of the alloying non-quenched and tempered steel

After finishing rolling, there are the α-Fe matrix, the solid solution α-Fe-C of C in α-Fe, the solid solution α-Fe-C-M of M in α-Fe-C, the solid solution α-Fe-M of M in α-Fe and the special carbide M_CC in microstructures. When pearlite is precipitated out, there is also the phase of Fe_3C in microstructures. When M_CC is not precipitated completely, there is also the solid solution α-Fe-C-M_C of M_C in α-Fe-C. The phase interfaces of microstructures include α-Fe/α-Fe-C, α-Fe/α-Fe-C-M, α-Fe/α-Fe-M, α-Fe/M_CC, and α-Fe-C/M_CC. When the pearlier is precipitated, there is the phase interface α-Fe/Fe_3C. When M_CC is not precipitated completely, there is the α-Fe/α-Fe-C-M_C phase interface.

1.2 Electron structure parameters of phases and phase interfaces

The covalent electron number n_A of the strongest bond in α-Fe was calculated in Ref. [6], and those of α-Fe-C, α-Fe-C-M and α-Fe-M were calculated in Refs. [7—9]. The phase interface electron density difference $\Delta\rho$ was calculated in Refs. [7, 10]. Because the content of carbon in the alloying non-quenched and tempered steel is lower than 0.25%, the electron structure parameters are calculated by 0.2% C. The calculated results are listed in Tables 1 and 2.

Table 1. Values of n_A of every phase in the alloying non-quenched and tempered steel (0.2% C)

Phase	n_A	Phase	n_A	Phase	n_A
α-Fe	0.3835	α-Fe-C-Cu	1.1733	α-Fe-Mo	0.7892
α-Fe-C	0.9012	α-Fe-C-V	2.6161	α-Fe-W	0.5017
α-Fe-C-Mn	1.2646	α-Fe-C-Nb	2.1419	α-Fe-Cu	0.4321
α-Fe-C-Si	1.3000	α-Fe-C-Ti	2.3620	α-Fe-V	0.4921
α-Fe-C-Cr	1.4956	α-Fe-Mn	0.4360	α-Fe-Nb	0.6358
α-Fe-C-Ni	1.3913	α-Fe-Si	0.4513	α-Fe-Ti	0.5675
α-Fe-C-Mo	2.4038	α-Fe-Cr	0.4853	Fe_3C	0.9672
α-Fe-C-W	2.1322	α-Fe-Ni	0.4934		

Table 2. Values of $\Delta\rho$ of every phase in the alloying non-quenched and tempered steel (0.2% C)[1)]

Phase interface	$\Delta\rho$	Phase interface	$\Delta\rho$	Phase interface	$\Delta\rho$
α-Fe/α-Fe-C	0.0354	α-Fe/α-Fe-C-Ti	0.0000	α-Fe/α-Fe-Ti	0.0009
α-Fe/α-Fe-C-Mn	0.0165	α-Fe/α-Fe-Mn	0.0004	α-Fe/Fe_3C	0.0004
α-Fe/α-Fe-C-Si	0.0174	α-Fe/α-Fe-Si	0.0016	α-Fe/TiC_1	29.5721
α-Fe/α-Fe-C-Cr	0.0082	α-Fe/α-Fe-Cr	0.0000	α-Fe/NbC_1	33.2494
α-Fe/α-Fe-C-Ni	0.0000	α-Fe/α-Fe-Ni	0.2424	α-Fe/VC_1	40.0625
α-Fe/α-Fe-C-Mo	0.0000	α-Fe/α-Fe-Mo	0.0001	α-Fe-C/TiC_2	12.3411
α-Fe/α-Fe-C-W	0.0000	α-Fe/α-Fe-W	0.0002	α-Fe-C/NbC_2	15.9920
α-Fe/α-Fe-C-Cu	0.0004	α-Fe/α-Fe-Cu	0.0005	α-Fe-C/VC_2	17.1793
α-Fe/α-Fe-C-V	0.0000	α-Fe/α-Fe-V	0.0002		
α-Fe/α-Fe-C-Nb	0.0000	α-Fe/α-Fe-Nb	0.0002		

1) M_CC_1 is the dispersion strengthening carbide; M_CC_2 is the precipitation strengthening carbide.

2 Strengthening mechanisms, coefficients and weights of the alloying non-quenched and tempered steel

From calculations of Ref. [5], the elongation of the non-quenched and tempered steel intensely depends on the strengthening mechanisms and the strengthening coefficients and strengthening weights. The strengthening coefficients and strengthening weights can be calculated with n_A and $\Delta\rho$. In the following subsections, the calculation formulas under different strengthening mechanisms are given.

2.1 Strengthening mechanisms and coefficients of the alloying non-quenched and tempered steel

The strengthening mechanisms of the non-quenched and tempered steel include rolling refinement, solution strengthening, interface strengthening, dispersion strengthening, and precipitation strengthening.

In Refs. [1—5], the ratio of $n_A^{\alpha\text{-Fe}}$ of the strongest bond of alloying phases to $n_A^{\alpha\text{-Fe}}$ of α-Fe is defined as the solution strengthening coefficient $S^{\alpha\text{-Fe}}$, i.e.

$$\left.\begin{aligned} S^{\alpha\text{-Fe-C}} &= n_A^{\alpha\text{-Fe-C}}/n_A^{\alpha\text{-Fe}} \\ S^{\alpha\text{-Fe-C-}M} &= n_A^{\alpha\text{-Fe-C-}M}/n_A^{\alpha\text{-Fe}} \\ S^{\alpha\text{-Fe-}M} &= n_A^{\alpha\text{-Fe-}M}/n_A^{\alpha\text{-Fe}} \end{aligned}\right\}. \quad (1)$$

The interface electron density difference $\Delta\rho$ matching the interface stress is defined as the interface strengthening coefficient B, i.e.

$$\left.\begin{aligned} B^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} &= \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \\ B^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M} &= \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M} \\ B^{\alpha\text{-Fe}/\alpha\text{-Fe-}M} &= \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-}M} \\ B^{\alpha\text{-Fe}/M_CC_1} &= \Delta\rho^{\alpha\text{-Fe}/M_CC_1} \\ B^{\alpha\text{-Fe-C}/M_CC_2} &= \Delta\rho^{\alpha\text{-Fe-C}/M_CC_2} \end{aligned}\right\}. \quad (2)$$

Here, S and B are the electron structure parameters which are inversely proportional to the elongation.

2.2 Strengthening weights of the alloying non-quenched and tempered steel

2.2.1 Solution strengthening weights

Because n_A of M_CC is very small (Table 3), M_CC can be precipitated out easily. Therefore, the atomic percentage of C to form the special carbide should be considered alone. Let the atomic percentage of C to participate in solution strengthening be C_S^C. Then

$$C_S^C = C^C - \sum C^{M_C}, \quad (3)$$

where C^C is the atomic percentage of C in the alloying non-quenched and tempered steel, C^{M_C} is the atomic percentage of carbide formation elements of V, Nb and Ti.

Table 3. n_A of austenite and special carbides of V, Nb and Ti in the non-quenched and tempered steel (0.2% C)

Phase	n_A	Phase	n_A
γ-Fe-C-Ti	1.1006	TiC	0.4020
γ-Fe-C-Nb	1.2186	NbC	0.5931
γ-Fe-C-V	1.0358	VC	0.6175

The weights of solution strengthening are

$$\left.\begin{aligned} W^{\alpha\text{-Fe-C}} &= \frac{C^C - \sum C^{M_C}}{n_A^{\alpha\text{-Fe-C}} + \sum n_A^{\alpha\text{-Fe-C-}M}} \cdot n_A^{\alpha\text{-Fe-C}} \\ W^{\alpha\text{-Fe-C-}M} &= \frac{C^C - \sum C^{M_C}}{n_A^{\alpha\text{-Fe-C}} + \sum n_A^{\alpha\text{-Fe-C-}M}} \cdot n_A^{\alpha\text{-Fe-C-}M} \\ W^{\alpha\text{-Fe-}M} &= C^M - W^{\alpha\text{-Fe-C-}M} \end{aligned}\right\}, \quad (4)$$

where C^M is the atomic percentage of alloying elements.

2.2.2 Interface strengthening weights

The weights of interface strengthening are equal to those of solution strengthening, i.e.

$$\left.\begin{aligned} W^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} &= W^{\alpha\text{-Fe-C}} \\ W^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M} &= W^{\alpha\text{-Fe-C-}M} \\ W^{\alpha\text{-Fe}/\alpha\text{-Fe-}M} &= W^{\alpha\text{-Fe-}M} \end{aligned}\right\}. \quad (5)$$

2.2.3 Dispersion strengthening weights

After being cooled, TiC, NbC and VC, which are dispersively precipitated out of austenite at high temperature rolling, will form the phase interface α-Fe/M_CC with the α-Fe matrix, on which the interface electron density difference is very large, and so the formed interface stress is very high and can result in strengthening, i.e. dispersion strengthening. To make a distinction from Ti(Nb, V)C out of α′-solid solution, the Ti(Nb, V)C out of austenite is denoted by M_CC_1. Their weights are

$$W^{M_CC_1} = \frac{C^C - C_S^C}{\sum n_A^{\gamma\text{-Fe-C-}M_C} + \sum n_A^{M_CC}} \cdot n_A^{M_CC}, \quad (6)$$

where the value of $C^C - C_S^C$ is also equal to $\sum C^{M_C}$, $n_A^{\gamma\text{-Fe-C-}M_C}$ is the covalent electron number of Ti, Nb and V in austenite (Table 3). The weight $W^{\gamma\text{-Fe-C-}M_C}$ of γ-Fe-C-M_C is

$$W^{\gamma\text{-Fe-C-}M_C} = \frac{C^C - C_S^C}{\sum n_A^{\gamma\text{-Fe-C-}M_C} + \sum n_A^{M_CC}} \cdot n_A^{\gamma\text{-Fe-C-}M_C}. \quad (7)$$

2.2.4 Precipitation strengthening weights

The rolling state with high temperature is nonequilibrium, Ti, Nb and V cannot be completely precipitated out of austenite to form Ti (Nb, V) C_1. A part of Ti, Nb and V will be dissolved in the γ-Fe-C austenite, and can also be precipitated out of α′-Fe-C-M_C during subsequently controlled rolling at two phase zones or cooled to form Ti (Nb, V) C. To distinguish from M_CC_1, Ti (Nb, V) C out of the α′-Fe-C-M_C is denoted by M_CC_2. On M_CC_2/α-Fe-C interfaces, the electron density difference $\Delta\rho$ is very large, that is, the interface stress is quite high. Therefore, the precipitation strengthening comes into

being. If Ti, Nb and V are completely precipitated out of α′-Fe-C-Ti (Nb, V), their weights are calculated by Eq. (7), i.e.

$$W^{M_CC_2} = W^{\gamma\text{-Fe-C-}M_C}. \tag{8}$$

If Ti, Nb and V cannot be completely precipitated out and partly dissolved in α-Fe-C, their weights are

$$\left.\begin{aligned} W^{M_CC_2} &= \frac{W^{\gamma\text{-Fe-C-}M_C}}{n_A^{\alpha\text{-Fe-C-}M_C} + n_A^{M_CC}} \cdot n_A^{M_CC} \\ W^{\alpha\text{-Fe-C-}M_C} &= \frac{W^{\gamma\text{-Fe-C-}M_C}}{n_A^{\alpha\text{-Fe-C-}M_C} + n_A^{M_CC}} \cdot n_A^{\alpha\text{-Fe-C-}M_C} \end{aligned}\right\}. \tag{9}$$

If Ti, Nb and V cannot form M_CC_2 and are completely dissolved in α-Fe-C, the weight $W^{\alpha\text{-Fe-C-}M_C}$ of α-Fe-C-Ti(Nb, V) is

$$W^{\alpha\text{-Fe-C-}M_C} = W^{\gamma\text{-Fe-C-}M_C}. \tag{10}$$

If VC_1 is not precipitated out, VC_2 is formed and part of V is still dissolved in α-Fe-C, their weights are

$$\left.\begin{aligned} W^{VC_2} &= \frac{C^V}{n_A^{\alpha\text{-Fe-C-V}} + n_A^{VC}} \cdot n_A^{VC} \\ W^{\alpha\text{-Fe-C-V}} &= C^V - W^{VC_2} \end{aligned}\right\}, \tag{11}$$

where C^V is the atomic percentage of V, which is equal to the atomic percentage of C to form VC. Accordingly C^V should be subtracted in Eqs. (6), (7).

In the controlled technologies of real production, the precipitation of M_CC is complex. The situations considered in this paper are just some common ones of precipitation.

3 Calculation of elongation of the alloying non-quenched and tempered steel

3.1 Elongation of the α-Fe matrix after rolling refinement

Liu et al.[5] have given the relation of the finishing rolling grain size D to the finishing rolling elongation $\delta^{\alpha\text{-Fe}}$ of α-Fe in non-quenched and tempered Si-Mn steel. The formula still fits for the alloying non-quenched and tempered steel, i.e.

$$\delta^{\alpha\text{-Fe}} = \delta_0 - \frac{\delta_0}{5.75\sqrt{D}}, \tag{12}$$

where δ_0 is the initial elongation of α-Fe, and its value is 50%.

3.2 Elongation decrements of solution strengthening

Because the elongation is inversely proportional to the solution strengthening coefficient S, the elongation decrements of solution strengthening are

$$\left.\begin{aligned} \Delta\delta^{\alpha\text{-Fe-C}} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-C}}}\right) W^{\alpha\text{-Fe-C}} \\ \Delta\delta^{\alpha\text{-Fe-C-}M} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-C-}M}}\right) W^{\alpha\text{-Fe-C-}M} \\ \Delta\delta^{\alpha\text{-Fe-}M} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-}M}}\right) W^{\alpha\text{-Fe-}M} \end{aligned}\right\}. \tag{13}$$

3.3 Elongation decrements of interface strengthening

Because the elongation decrement is directly proportional to the interface strengthening coefficient B, the elongation decrements of phase interfaces are

$$\left.\begin{aligned} \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \cdot W^{\alpha\text{-Fe-C}} \\ \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M} \cdot W^{\alpha\text{-Fe-C-}M} \\ \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-}M} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-}M} \cdot W^{\alpha\text{-Fe-}M} \end{aligned}\right\}. \tag{14}$$

3.4 Elongation decrements of dispersion strengthening

When the dispersion strengthening comes into being, the interface electron density difference $\Delta\rho$ is very large. Under the first order of approximation ($\Delta\rho < 10\%$), the electron density is discontinuous, i.e. $\sigma = 0$. Over the first order of approximation, although the electron density is continuous again, the continuous number σ' is small. Compared with the interface between the matrix and solid solution, the above interface is of high stress and low plasticity. Taken the interfaces between α-Fe and the solid solutions of Mn and Si as an example, the difference between the α-Fe/M_CC_1 dispersion strengthening interface and the solution strengthening interface is explained.

Therefore, the influencing amount of dispersion strengthening on elongation can not be calculated by Eq. (14). Taken the interface electron density difference $\Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}$ and the elongation decrement $\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}$ on the α-Fe/α-Fe-C basic interface as references, the influencing amount of the dispersion strengthening on elongation can be achieved by comparing the interface density difference $\Delta\rho^{\alpha\text{-Fe}/M_CC_1}$ on

the α-Fe/M_CC_1 interfaces to that of α-Fe/α-Fe-C interface. Hence, the finishing rolling elongation decrements of dispersion strengthening can be expressed as

$$\Delta\delta^{\alpha\text{-Fe}/M_CC_1} = \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \frac{\Delta\rho^{\alpha\text{-Fe}/M_CC_1}}{\Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}} W^{M_CC_1}, \tag{15}$$

where $W^{M_CC_1}$ is equal to different values according to differently controlled technologies.

3.5 Elongation decrements of precipitation strengthening

When the precipitation strengthening comes into being, the interface density difference is still large, but it is smaller than that of dispersion strengthening. Under the first order of approximation, σ is equal to 0. Over the first order of approximation, the electron density is continuous again, and σ' is much larger than σ of the phase interface α-Fe/α-Fe-C (Table 4). Obviously, the plasticity of phase interfaces is better than that of dispersion strengthening.

Table 4. Comparisons of σ, σ', $\Delta\rho$ between solution strengthening interfaces and the dispersion and precipitation strengthening interfaces (0.2% C)

Phase interface	Interface electron density ρ	σ	σ'	$\Delta\rho$(%)
α-Fe/α-Fe-C	29.1077/29.0723	5751	0	0.12
α-Fe/α-Fe-C-Mn	29.1077/29.0912	6150	0	5.7×10^{-2}
α-Fe/α-Fe-C-Si	29.1077/29.0903	1395	0	6.0×10^{-2}
α-Fe/α-Fe -Mn	29.4314/29.4310	3294	0	1.32×10^{-2}
α-Fe/α-Fe-Si	30.8947/30.8931	1586	0	4.93×10^{-5}
α-Fe/TiC_1	4.4903/34.0624	0	60	153.40
α-Fe/NbC_1	4.4903/37.7143	0	54	157.4
α-Fe/VC_1	4.4903/44.5528	0	51	163.40
α-Fe-C/TiC_2	21.7476/34.0624	0	38340	44.13
α-Fe-C/NbC_2	21.7476/37.7396	0	69012	53.77
α-Fe-C/VC_2	39.2655/21.7476	0	103518	57.42

The finishing rolling elongation decrements of precipitation strengthening are

$$\left.\begin{aligned}
&\Delta\delta^{\alpha\text{-Fe-C}/M_CC_2} \\
&\quad = \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \cdot \frac{\Delta\rho^{\alpha\text{-Fe-C}/M_CC_2}}{\Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}} \cdot W^{M_CC_2} \\
&\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M_C} \\
&\quad = \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M_C} \cdot W^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M_C} \\
&\Delta\delta^{\alpha\text{-Fe-C-}M_C} = \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-C-}M_C}}\right) W^{\alpha\text{-Fe-C-}M_C}
\end{aligned}\right\}, \tag{16}$$

where $W^{M_CC_2}$ and $W^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M_C}$ are substituted for the according weight of Eqs. (8)—(11) based on differently controlled technologies.

4 Calculation of the finishing rolling elongation in alloying non-quenched and tempered steel

The finishing rolling elongation of the alloying non-quenched and tempered steel is subtracting all the elongation decrements of solution strengthening, interface strengthening, dispersion strengthening and precipitation strengthening from the refined α-Fe matrix. Therefore,

$$\begin{aligned}
\delta = {} & \delta^{\alpha\text{-Fe}} \cdot C^{Fe} - \Delta\delta^{\alpha\text{-Fe-C}} \\
& - \sum\Delta\delta^{\alpha\text{-Fe-C-}M} - \sum\Delta\delta^{\alpha\text{-Fe-}M} - \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \\
& - \sum\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M} - \sum\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-}M} \\
& - \sum\Delta\delta^{\alpha\text{-Fe}/M_CC_1} - \sum\Delta\delta^{\alpha\text{-Fe-C}/M_CC_2} \\
& - \sum\Delta\delta^{\alpha\text{-Fe-C-}M_C} - \sum\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M_C} \\
& + \Delta\delta^{max},
\end{aligned} \tag{17}$$

where C^{Fe} is the atomic percentage of Fe, $\Delta\delta^{max}$ is the maximum value of all elongation decrements in phases or phase interfaces.

5 Calculation of the finishing rolling elongation with the precipitation of pearlite

The pearlite can be precipitated out of austenite, and because of slower cooling it can also be precipitated by way of self-temper after crimping. The elongation and strength are nearly the same under the above two circumstances, and we only discuss the former in this paper. The n_A of austenite with alloying elements are given in Table 5. The calculation methods are given in Refs. [7, 9].

Table 5. Values of n_A of alloying austenite phases (0.2% C)

Phase	n_A	Phase	n_A
γ-Fe-C	1.0504	γ-Fe-C-Mo	1.0424
γ-Fe-C-Mn	1.0936	γ-Fe-C-W	1.1816
γ-Fe-C-Si	1.2809	γ-Fe-C-Cu	1.2937
γ-Fe-C-Cr	1.0463	γ-Fe-C-Ni	1.3638

In Table 5, the n_A of the structure units of γ-Fe-C, γ-Fe-C-Mn and γ-Fe-C-Cr are small and near. Therefore, after finishing rolling pearlite can be precipitated out of austenite units of γ-Fe-C and γ-Fe-C-Mn in the non-quenched and tempered steel. Because the element of Cr can increase hardenability and affect the welding performance of the non-quenched and tempered steel, the element of Cr is not or little put

into steel. Therefore, the precipitation of pearlite from γ-Fe-C-Cr austenite unit is not discussed in this paper.

5.1 Calculation of the finishing rolling elongation with pearlite out of γ-Fe-C

When the pearlite is precipitated out of γ-Fe-C austenite, the weight $W_{P\text{-}C}^{\gamma\text{-}Fe\text{-}C}$ of peralite and the weights $W_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C}$ and $W_{P\text{-}C}^{Fe_3C}$ of α-Fe-C and Fe_3C in pearlite and the weights $W_{P\text{-}C}^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C}$, $W_{P\text{-}C}^{\alpha\text{-}Fe/Fe_3C}$ of α-Fe/α-Fe-C and α-Fe/Fe_3C are

$$\left.\begin{aligned} W_{P\text{-}C}^{\gamma\text{-}Fe\text{-}C} &= \frac{C_S^C}{n_A^{\gamma\text{-}Fe\text{-}C} + \sum n_A^{\gamma\text{-}Fe\text{-}C\text{-}M}} \cdot n_A^{\gamma\text{-}Fe\text{-}C} \\ W_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C} &= \frac{W_{P\text{-}C}^{\gamma\text{-}Fe\text{-}C}}{n_A^{\alpha\text{-}Fe\text{-}C} + n_A^{Fe_3C}} \cdot n_A^{\alpha\text{-}Fe\text{-}C} \\ W_{P\text{-}C}^{Fe_3C} &= \frac{W_{P\text{-}C}^{\gamma\text{-}Fe\text{-}C}}{n_A^{\alpha\text{-}Fe\text{-}C} + n_A^{Fe_3C}} \cdot n_A^{Fe_3C} \\ W_{P\text{-}C}^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C} &= W_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C} \\ W_{P\text{-}C}^{\alpha\text{-}Fe/Fe_3C} &= W_{P\text{-}C}^{Fe_3C} \end{aligned}\right\}. \quad (18)$$

Because the structure unit of γ-Fe-C-M cannot be transformed into pearlite, after finishing rolling the weight of α-Fe-C-M structure unit is equal to that of γ-Fe-C-M, i.e.

$$\left.\begin{aligned} W^{\alpha\text{-}Fe\text{-}C\text{-}M} &= W^{\gamma\text{-}Fe\text{-}C\text{-}M} \\ &= \frac{C_S^C}{n_A^{\gamma\text{-}Fe\text{-}C} + \sum n_A^{\gamma\text{-}Fe\text{-}C\text{-}M}} \cdot n_A^{\gamma\text{-}Fe\text{-}C\text{-}M} \\ W^{\alpha\text{-}Fe\text{-}M} &= C^M - W^{\alpha\text{-}Fe\text{-}C\text{-}M} \end{aligned}\right\}, \quad (19)$$

where C^M is the atomic percentage of alloying element.

The finishing rolling elongation decrements of solution strengthening are

$$\left.\begin{aligned} \Delta\delta^{\alpha\text{-}Fe\text{-}C\text{-}M} &= \delta^{\alpha\text{-}Fe}\left(1 - \frac{1}{S^{\alpha\text{-}Fe\text{-}C\text{-}M}}\right) W^{\alpha\text{-}Fe\text{-}C\text{-}M} \\ \Delta\delta^{\alpha\text{-}Fe\text{-}M} &= \delta^{\alpha\text{-}Fe}\left(1 - \frac{1}{S^{\alpha\text{-}Fe\text{-}M}}\right) W^{\alpha\text{-}Fe\text{-}M} \end{aligned}\right\}. \quad (20)$$

The elongation decrements caused by the precipitation of pearlite are

$$\left.\begin{aligned} \Delta\delta_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C} &= \delta^{\alpha\text{-}Fe}\left(1 - \frac{1}{S^{\alpha\text{-}Fe\text{-}C}}\right) W_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C} \\ \Delta\delta_{P\text{-}C}^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C} &= \delta^{\alpha\text{-}Fe}\Delta\rho^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C} W_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C} \\ \Delta\delta_{P\text{-}C}^{\alpha\text{-}Fe/Fe_3C} &= \delta^{\alpha\text{-}Fe}\Delta\rho^{\alpha\text{-}Fe/Fe_3C} W^{Fe_3C} \end{aligned}\right\}. \quad (21)$$

The finishing rolling elongation decrements of interface strengthening are

$$\left.\begin{aligned} \Delta\delta^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C\text{-}M} &= \delta^{\alpha\text{-}Fe}\Delta\rho^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C\text{-}M} W^{\alpha\text{-}Fe\text{-}C\text{-}M} \\ \Delta\delta^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}M} &= \delta^{\alpha\text{-}Fe}\Delta\rho^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}M} W^{\alpha\text{-}Fe\text{-}M} \end{aligned}\right\}. \quad (22)$$

The finishing rolling elongation decrements of dispersion strengthening and precipitation strengthening are calculated by Eqs. (15), (16).

Therefore, the finishing rolling elongation of the alloying non-quenched and tempered steel with pearlite out of γ-Fe-C austenite is

$$\begin{aligned} \delta = {} & \delta^{\alpha\text{-}Fe} \cdot C^{Fe} - \sum \Delta\delta^{\alpha\text{-}Fe\text{-}C\text{-}M} \\ & - \sum \Delta\delta^{\alpha\text{-}Fe\text{-}M} - \Delta\delta_{P\text{-}C}^{\alpha\text{-}Fe\text{-}C} - \Delta\delta_{P\text{-}C}^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C} \\ & - \Delta\delta_{P\text{-}C}^{\alpha\text{-}Fe/Fe_3C} - \sum \Delta\delta^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C\text{-}M} \\ & - \sum \Delta\delta^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}M} - \sum \Delta\delta^{\alpha\text{-}Fe/M_CC_1} \\ & - \sum \Delta\delta^{\alpha\text{-}Fe\text{-}C/M_CC_2} - \sum \Delta\delta^{\alpha\text{-}Fe\text{-}C\text{-}M_C} \\ & - \sum \Delta\delta^{\alpha\text{-}Fe/\alpha\text{-}Fe\text{-}C\text{-}M_C} + \Delta\delta^{max}. \end{aligned} \quad (23)$$

5.2 Calculation of the finishing rolling elongation in the alloying non-quenched and tempered steel with the pearlite out of γ-Fe-C and γ-Fe-C-Mn

The calculation of the finishing rolling elongation with pearlite precipitated out of γ-Fe-C structure unit is the same as the above-mentioned one. When the pearlite is precipitated out of γ-Fe-C-Mn structure unit, the weight of pearlite is

$$W_{P\text{-}C}^{\gamma\text{-}Fe\text{-}C\text{-}Mn} = \frac{C_S^C}{n_A^{\gamma\text{-}Fe\text{-}C} + \sum n_A^{\gamma\text{-}Fe\text{-}C\text{-}M}} \cdot n_A^{\gamma\text{-}Fe\text{-}C\text{-}Mn}. \quad (24)$$

In pearlite, the strengthening weights of α-Fe-C-Mn and Fe_3C are

$$\left.\begin{aligned} W_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} &= \frac{W_{\text{P-C}}^{\gamma\text{-Fe-C-Mn}}}{n_{\text{A}}^{\alpha\text{-Fe-C-Mn}} + n_{\text{A}}^{\text{Fe}_3\text{C}}} \cdot n_{\text{A}}^{\alpha\text{-Fe-C-Mn}} \\ W_{\text{P-Mn}}^{\text{Fe}_3\text{C}} &= \frac{W_{\text{P-C}}^{\gamma\text{-Fe-C-Mn}}}{n_{\text{A}}^{\alpha\text{-Fe-C-Mn}} + n_{\text{A}}^{\text{Fe}_3\text{C}}} \cdot n_{\text{A}}^{\text{Fe}_3\text{C}} \end{aligned}\right\}. \tag{25}$$

When Fe_3C is formed, there is Mn out of γ-Fe-C-Mn, and the precipitated Mn will be dissolved into α-Fe again, its weight is

$$W_{\text{P-Mn}}^{\alpha\text{-Fe-Mn}'} = W_{\text{P-Mn}}^{\text{Fe}_3\text{C}}. \tag{26}$$

The interface weights after the precipitation of pearlite are

$$\left.\begin{aligned} W_{\text{P-Mn}}^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Mn}} &= W_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} \\ W_{\text{P-Mn}}^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} &= W_{\text{P-Mn}}^{\text{Fe}_3\text{C}} \\ W_{\text{P-Mn}}^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}'} &= W_{\text{P-Mn}}^{\text{Fe}_3\text{C}} \end{aligned}\right\}. \tag{27}$$

For being clear, $\bar{M}$ denotes the other elements when the structure unit of γ-Fe-C-Mn is transformed into pearlite. Because the structure unit of γ-Fe-C-$\bar{M}$ is not transformed into pearlite, the weight of α-Fe-C-$\bar{M}$ is equal to that of γ-Fe-C-$\bar{M}$ after finishing rolling, i.e.

$$\left.\begin{aligned} W^{\alpha\text{-Fe-C-}\bar{M}} &= W^{\gamma\text{-Fe-C-}\bar{M}} \\ &= \frac{C_{\text{S}}^{\text{C}}}{n_{\text{A}}^{\gamma\text{-Fe-C}} + \sum n_{\text{A}}^{\gamma\text{-Fe-C-}\bar{M}}} \cdot n_{\text{A}}^{\gamma\text{-Fe-C-}\bar{M}} \\ W^{\alpha\text{-Fe-}\bar{M}} &= C^{\bar{M}} - W^{\alpha\text{-Fe-C-}\bar{M}} \\ W^{\alpha\text{-Fe-Mn}} &= C^{\text{Mn}} - W_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} \end{aligned}\right\}. \tag{28}$$

The finishing rolling elongation decrements of solution strengthening are

$$\left.\begin{aligned} \Delta\delta^{\alpha\text{-Fe-C-}\bar{M}} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-C-}\bar{M}}}\right) W^{\alpha\text{-Fe-C-}\bar{M}} \\ \Delta\delta^{\alpha\text{-Fe-}\bar{M}} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-}\bar{M}}}\right) W^{\alpha\text{-Fe-}\bar{M}} \\ \Delta\delta^{\alpha\text{-Fe-Mn}} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-Mn}}}\right) W^{\alpha\text{-Fe-Mn}} \end{aligned}\right\}. \tag{29}$$

The finishing rolling elongation decrements caused by the precipitation of pearlite are

$$\left.\begin{aligned} \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe-C}} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-C}}}\right) W_{\text{P-C}}^{\alpha\text{-Fe-C}} \\ \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-C-Mn}}}\right) W_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} \\ \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe-Mn}'} &= \delta^{\alpha\text{-Fe}}\left(1 - \frac{1}{S^{\alpha\text{-Fe-Mn}}}\right) W^{\alpha\text{-Fe-Mn}'} \\ \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \cdot W_{\text{P-C}}^{\alpha\text{-Fe-C}} \\ \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Mn}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Mn}} \cdot W_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} \\ \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} \cdot W_{\text{P-C}}^{\text{Fe}_3\text{C}} \\ \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} \cdot W_{\text{P-Mn}}^{\text{Fe}_3\text{C}} \\ \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}'} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}} \cdot W_{\text{P-Mn}}^{\text{Fe}_3\text{C}} \end{aligned}\right\}. \tag{30}$$

The finishing rolling elongation decrements of interface strengthening are

$$\left.\begin{aligned} \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}\bar{M}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}\bar{M}} \cdot W^{\alpha\text{-Fe-C-}\bar{M}} \\ \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-}\bar{M}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-}\bar{M}} \cdot W^{\alpha\text{-Fe-}\bar{M}} \\ \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}} &= \delta^{\alpha\text{-Fe}} \cdot \Delta\rho^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}} \cdot W^{\alpha\text{-Fe-Mn}} \end{aligned}\right\}. \tag{31}$$

The finishing rolling elongation decrements of dispersion strengthening and precipitation strengthening are calculated by the above-mentioned methods.

Therefore, the finishing rolling elongation of the alloying non-quenched and tempered steel with pearlite precipitated simultaneously out of γ-Fe-C and γ-Fe-C-Mn is

$$\begin{aligned} \delta = {} & \delta^{\alpha\text{-Fe}} \cdot C^{\text{Fe}} - \sum \Delta\delta^{\alpha\text{-Fe-C-}\bar{M}} \\ & - \sum \Delta\delta^{\alpha\text{-Fe-}\bar{M}} - \Delta\delta^{\alpha\text{-Fe-Mn}} - \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe-C}} \\ & - \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe-C-Mn}} - \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe-Mn}'} - \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe}/\alpha\text{-Fe-C}} \\ & - \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Mn}} - \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}'} - \Delta\delta_{\text{P-C}}^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} \\ & - \Delta\delta_{\text{P-Mn}}^{\alpha\text{-Fe}/\text{Fe}_3\text{C}} - \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}} - \sum \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}\bar{M}} \\ & - \sum \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-}\bar{M}} - \sum \Delta\delta^{\alpha\text{-Fe}/M_{\text{C}}C_1} \\ & - \sum \Delta\delta^{\alpha\text{-Fe-C}/M_{\text{C}}C_2} - \sum \Delta\delta^{\alpha\text{-Fe-C-}M_{\text{C}}} \\ & - \sum \Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-}M_{\text{C}}} + \Delta\delta^{\max}. \end{aligned} \tag{32}$$

6 Examples for calculation

In this section, X52, X60 and X65 produced in some factories are taken as examples for calculation; the calculated and measured values are listed in Table 6. Obviously, the calculated results agree well with

the measured ones.

Table 6. Comparison between the measured and the calculated results (σ_b, σ_s: MPa; δ: %; α_K: J)

Steel number	Production date	Furnace number	Lot number	Chemical composition	Measured values						Calculated results				Rolling technology	Rolling scales
					σ_s	σ_b	δ		α_K		σ_s	σ_b	δ	α_K		
X52	2003-1-28	DL03 30552	B030 12401A	1)	525	595	31	85	100	92	533	592	30	92	1	12
X52	2003-2-3	DL03 10834	B030 13032A	2)	505	565	30	80	90	90	509	570	31	94	1-1	11.5
X60	2003-1-31	DL03 10640	B030 102332	3)	510	585	30	88	100	86	516	579	30	91	1	12
X60	2003-2-10	DL03 11031	B030 20676B	4)	550	610	30	74	74	86	552	618	29	86	1	12
X65	10-2-05	30964	09622S	5)	535	605	36.5	84	90	80	531	603	38	87	1-1	12
X65	19-2-05	21232	18771S	6)	540	635	40	200	198	190	540	644	39	212	3	9
X65	10-2-05	30965		7)	540	610	37.5	76	80	84	539	600	36	83	1	12
X65	7-2-05	20911		8)	510	580	40	164	154	152	512	576	41.5	166	2	10

Chemical compositions (wt %): 1) C=0.070, Si=0.280, Mn=1.310, P=0.014, S=0.003, Al= 0.040, Nb=0.030, Ti=0.020, V=0.040; 2) C=0.080, Si=0.260, Mn=1.250, P= 0.014, S=0.003, Al=0.030, Nb=0.030, Ti=0.020, V=0.030; 3) C=0.080, Si=0.220, Mn=1.320, P=0.012, S=0.001, Al=0.020, Nb=0.030, Ti=0.010, V=0.040; 4) C=0.080, Si=0.240, Mn=1.370, P=0.014, S=0.003, Al=0.030, Nb=0.040, Ti=0.020, V=0.030; 5) C=0.090, Si=0.240, Mn=1.480, P=0.013, S=0.005, N=0.004, Nb=0.038, Ti=0.010, V=0.039; 6) C=0.060, Si=0.190, Mn=1.480, P=0.012, S=0.003, N=0.042, Nb= 0.050, Ti=0.010, V=0.050, Ni=0.16, Mo=0.18, Cu=0.300; 7) C=0.08, Si=0.25, Mn=1.44, P=0.013, S=0.006, Nb=0.04, V=0.04, Ti=0.01, N=0.0033; 8) C=0.08, Si=0.24, Mn=1.48, P=0.011, S=0.005, Nb=0.04, V=0.04, Ti=0.01, N=0.0031.

Rolling technologies: 1: NQTS-$(TN)_1$-(TNV)SR, TiC_1 and NbC_1 are precipitated out during high temperature rolling, the Ti, Nb and V are dissolved in α-Fe-C after finishing rolling. NQTS represses the non-quenched and tempered steel, T denotes Ti, N denotes Nb, $(TN)_1$ denotes Ti(Nb) C_1 precipitated out at high temperature rolling, SR denotes solution, (TNV)SR denotes that parts of Ti, Nb and V are dissolved after finishing rolling; 1-1: NQTS-$(TN)_1$-(TNV)SR-Cp, there is the precipitation of pearlite from γ-Fe-C austenite in rolling technology one, the precipitation of pearlite from γ-Fe-C austenite is denoted by Cp; 2: NQTS-$(TN)_{12}$-VSR-CpMnp, TiC_1, NbC_1, TiC_2 and NbC_2 are precipitated out during hot rolling, and V is dissolved in α-Fe-C after finishing rolling, γ-Fe-C and γ-Fe-C-Mn are simultaneously decomposed into pearlite, the precipitation of pearlite from γ-Fe-C and γ-Fe-C-Mn austenite is denoted by CpMnp; 3: NQTS-$(TN)_{12}V_2$-VSR-CpMnp, TiC_1, NbC_1, TiC_2, NbC_2 and VC_2 are precipitated out during hot rolling, and the rest V is dissolved in α-Fe-C after finishing rolling, γ-Fe-C and γ-Fe-C-Mn are simultaneously decomposed into pearlite.

Because the accuracy of stretcher and the experimental condition are different, the deviation between the calculated values and the measured ones often appears.

For the composition of 5(X65), all the $\Delta\delta$ of phases and phase interfaces are calculated (Table 7). $\Delta\delta^{Max}$ is equal to $\Delta\delta^{\alpha\text{-Fe-Mn}}$, i.e. $\Delta\delta^{Max} = \Delta\delta^{\alpha\text{-Fe-Mn}} = 7.6451$. If all the values in Table 7 are substituted into Eq. (17), we will achieve $\delta = 29.8848$, which is different from the measured value of $\delta = 36.5$ by 6.6152. Note from Table 7 that $\Delta\delta^{\alpha\text{-Fe-C-Mn}}$ and $\Delta\delta^{\alpha\text{-Fe-C-Si}}$ are equal to 3.9910 and 4.1514, respectively. And the sum of them is 8.1424, which is close to $\Delta\delta^{\alpha\text{-Fe-Mn}} = 7.6451$. By adding 8.1424 to 29.8848, we can achieve $\delta = 38.0272$, which agrees well with the measured one. The reason for error is that the stretcher cannot distinguish the tiny difference between $\Delta\delta^{\alpha\text{-Fe-C-Mn}}$ and $\Delta\delta^{\alpha\text{-Fe-C-Si}}$, and take α-Fe-C-Mn and α-Fe-C-Si as one structure unit. Similarly, the stretcher cannot distinguish the difference between $\Delta\delta^{max} = 7.6451$ and $\Delta\delta^{max} = 8.1424$. Therefore, the calculated result cannot agree well with the measured one. However, the above deviation can be eliminated during calculation.

Table 7. Calculation of elongation of X65 steel

Elongation decrements of phases		Elongation decrements of phase interfaces		Elongation decrements of phase interfaces of carbides	
$\Delta\delta^{\alpha\text{-Fe-C}}$	1.1310	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}$	6.97×10^{-2}	$\Delta\delta^{\alpha\text{-Fe}/TiC_1}$	0.2422
$\Delta\delta^{\alpha\text{-Fe-C-Mn}}$	3.9910	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Mn}}$	9.45×10^{-2}	$\Delta\delta^{\alpha\text{-Fe}/NbC_1}$	0.4017
$\Delta\delta^{\alpha\text{-Fe-C-Si}}$	4.1514	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Si}}$	0.1025		
$\Delta\delta^{\alpha\text{-Fe-C-Nb}}$	0.6296	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Nb}}$	0.0000		
$\Delta\delta^{\alpha\text{-Fe-C-V}}$	1.6788	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-V}}$	0.0000		
$\Delta\delta^{\alpha\text{-Fe-C-Ti}}$	0.2880	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Ti}}$	0.0000		
$\Delta\delta^{\alpha\text{-Fe-Mn}}$	7.6451	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}}$	2.54×10^{-2}		
$\Delta\delta^{\alpha\text{-Fe-Si}}$	2.4140	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-Si}}$	2.57×10^{-2}		

For the composition of 4 (X60), all the $\Delta\delta$ are listed in Table 8. $\Delta\delta^{Max}$ is equal to $\Delta\delta^{\alpha\text{-Fe-Mn}}$, i.e. $\Delta\delta^{max} = \Delta\delta^{\alpha\text{-Fe-Mn}} = 7.1270$. The sum of $\Delta\delta^{\alpha\text{-Fe-C-Mn}}$ and $\Delta\delta^{\alpha\text{-Fe-C-Si}}$ is equal to 6.9627, i.e. 3.4128 + 3.5499 = 6.9627. Although the value of 6.9627 is close to $\Delta\delta^{max}$, the stretcher distinguishes the difference between $\Delta\delta^{\alpha\text{-Fe-C-Mn}}$ and $\Delta\delta^{\alpha\text{-Fe-C-Si}}$, and so the circumstance similar to 5 (X65) does not appear. Therefore, the calculated value of $\delta = 29.2041$ agrees well with the measured one of $\delta = 30$.

Table 8. Calculation of elongation of X60 steel

Elongation decrements of phases		Elongation decrements of phase interfaces		Elongation decrements of phase interfaces of carbides	
$\Delta\delta^{\alpha\text{-Fe-C}}$	2.0052	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C}}$	0.1236	$\Delta\delta^{\alpha\text{-Fe}/TiC_1}$	0.5895
$\Delta\delta^{\alpha\text{-Fe-C-Mn}}$	3.4128	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Mn}}$	8.08×10^{-2}	$\Delta\delta^{\alpha\text{-Fe}/NbC_1}$	0.9778
$\Delta\delta^{\alpha\text{-Fe-C-Si}}$	3.5499	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Si}}$	0.0876		
$\Delta\delta^{\alpha\text{-Fe-C-Nb}}$	0.5882	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Nb}}$	0.0000		
$\Delta\delta^{\alpha\text{-Fe-C-V}}$	1.2916	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-V}}$	0.0000		
$\Delta\delta^{\alpha\text{-Fe-C-Ti}}$	0.6774	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-C-Ti}}$	0.0000		
$\Delta\delta^{\alpha\text{-Fe-Mn}}$	7.1270	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-Mn}}$	2.37×10^{-2}		
$\Delta\delta^{\alpha\text{-Fe-C-Si}}$	2.5428	$\Delta\delta^{\alpha\text{-Fe}/\alpha\text{-Fe-Si}}$	2.71×10^{-2}		

7 Conclusions

In the alloying non-quenched and tempered steel used in engineering, the element of Cr is not contained. Because of the shortage of measured data of steel with Cr, the calculation of elongation in the alloying non-quenched and tempered steel without the element of Cr is discussed in this paper. When the steel contains the element of Cr, the calculation methods are the same as the ones in this paper. The calculation formulas in this paper have been integrated with those of finishing rolling impact work of the alloying non-quenched and tempered steel delivered in another paper. We need only substitute the chemical composition, grain size scale and rolling technology into the calculation formula, then the values of σ_s, σ_b, δ and α_k can be easily obtained.

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