Modelling of microstructure development for thermomechanical rolling in (α+β) temperature range

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The main task of investigation was the choice of empirical equations to construct a model that most effectively reflect the real material response accompanying the microstructure development during controlled rolling of niobium microalloyed steel at finishing rolling temperature within (α+γ) range. Finishing rolling at decreasing temperature into the austenite–ferrite two-phase region was considered as the most effective in grain refinement of ferrite-pearlite microstructure formed at the last stages of deformation and on cooling after rolling.

The applied model for the austenite structure development during hot rolling of microalloyed steels has been described elsewhere [1]. The modelling of a strain-induced precipitation of niobium carbonitride during rolling of microalloyed steel for shipbuilding industry was given by Sellars [2,3].

From the analyses of existing models of austenite phase transformations, it was assumed that we can adopt an isothermal transformation kinetics and the principle of additivity rule for calculation of the progress of (α+γ) transformation [4].

Austenite to ferrite transformation start temperature Ts was established according to the following formula (1) [5]:

$$Ts = A - 19Cr^{0,481} - 0,5\exp[\frac{7,8 + 0,042D_{\gamma}}{(2,11 + \varepsilon_{\gamma})^{1,35}}] \qquad [K] \tag{1}$$

where: A - constant that depends only on the steel chemical composition (taken as A=1093)
Cr – cooling rate [K/s]
D_{γ} - austenite grain size [μm]
E_{γ} - retained strain in unrecrystallized austenite.

It is obvious that retained strain in unrecrystallized austenite will increase Ts temperature for a given cooling rate. On the other hand the purpose of increasing cooling rate is to lower the transformation temperature and build up of driving force for austenite decomposition and increase in the ferrite nucleation probability.

The suppressed growth rate of ferrite with increased cooling rate influence further grain refinement of proeutectoid ferrite and reduces the time of transformation γ→α may be reduced. Rolling at austenite to ferrite temperature region usually produces the pancake like

austenite structure, which leads to mixed microstructure of coarse and fine polygonal ferrite grains. From coarse – grained austenite coarse polygonal ferrite or Widmanstätten ferrite and then bainite is formed with the cooling rate increase above 5 K/s. Regions of fine-grained austenite will transform into small polygonal ferrite and the dispersion of banded pearlite grains because Ts temperature varies only slightly within 20 deg.

At low finishing rolling temperatures below 1073 K niobium precipitation accelerates the onset of $\gamma \rightarrow \alpha$ transformation may rise Ts while the progress of transformation will be retarded. As concluded elsewhere [7,8] at low strain the decrease of the Ts describes the hardenability properties of niobium which is in solution in austenite but that vanishes at high strains [9,10].

Progress of the austenite – ferrite transformation taking into account the effect of austenite grain size is given by equation (2):

$$X = 1 - \exp(-b \frac{t^n}{D_\gamma^m})$$ (2)

where: X – transformed fraction of austenite
t – isothermal holding time
D_γ - austenite grain size
b- the nucleation and growth rate constant that depends only on transformation temperature
n – parameter related to the geometry of the growing phase and conditions of nucleation
m – empirically determined constant proportional to the total number of nucleation sites available; 1- for grain surface; 2 – for edge; 3- for corner nucleation for any nucleation rate.

When rolling in the two – phase region modelling of the ferrite microstructure starts to be more complex because deformation temperature is usually higher than recrystallization start temperature for ferrite. This implies that when the deformation conditions are below Ts the ferrite recrystallization can be observed. Thus the ferrite grain size is calculated using equation (3) when formed from nonrecrystallized austenite region.

$$dF_{rex} = 0,0281 dF^{2,42} \varepsilon_r^{-0,942} Z^{-0,0228}$$ (3)

where: dF – the initial ferrite grain size from nonrecrystallized austenite region
ε_r – strain accumulated in ferrite (the retained strain)
Z – Zener – Hollmon parameter.

Including the effect of retained strain ε_r on ferrite grain size (4):

$$dF = d_{\gamma rex}(1 - 0,45\varepsilon_r^{1/2})$$ (4)

According to Sellars and Beynon [11] the ferrite grain size formed from the recrystallized austenite structure is given (5):

$$dF = a + bCr^{-0,5} + C[1 - \exp(-1,5 \cdot 10^{-2} D_\gamma)]$$ (5)

where: a, b, c – material constants for C-Mn, Nb and Ti+V steels respectively: a=1.4; 2.5; 3; b=5; 3; 1.4; c=22; 20; 17. For ferrite grain size with no retained strain the equation (6) was development from limited rolling experiment, which was based on a model proposed by Sellars and Beynon [11,12]. This model has been subsequently tasted by Hodgson [13] on a much wider range of steel compositions: 0,06÷0,2%C; 0,2÷1,4%Mn; 0÷0,3%Si; to 0,02Ti, 0÷0,06%V, 0÷0,06%Nb and found to be very accurate.

$$dF_o = (-0,4 + 6,4C_E) + (2,4 - 59C_E)Cr^{-0,5} + 22[1 - \exp(-0,015d\gamma)] \tag{6}$$

where: $C_E = C + \dfrac{Mn}{6}$ when $C_E < 0,35$

C_r – cooling rate [K/s]

$D\gamma$ - austenite grain size (µm)

  Above $C_E \approx 0,35$ the equation (6) becomes (7):

$$dF_o = (-22,6 - 57C_E + 3Cr^{-0,5} + 22[1 - \exp(-0,015d\gamma)] \tag{7}$$

The sensitivity to cooling rates decreases at higher C_E values. These models have been extensively validated for plate, rod, structural and bar mills where the cooling rate was in the range 0,2÷5K/s and the mean austenite grain size was between 10÷60µm.

For Nb microalloyed steels, which can accumulate much higher levels of retained strain it has been extremely difficult o develop a general expression. Hodgson proposed the equation (8) for Nb steels valid for chemical composition within: 0,04÷0,15%C, 08÷1,2%Mn, 0,02÷0,04%Nb and cooling rates: 0,3÷10K/s with initial austenite grain sizes of 15~90µm.

$$dF = (1 - 0,8\varepsilon_r^{0,15})(29 - 5Cr^{-0,5} + 10[1 - \exp(-0,015d\gamma)] \tag{8}$$

More recently, a number of authors have attempted to develop equations based on the physical progress of nucleation and growth theory [14÷16]. However, these still generally involve a large degree of empiricism and significantly more research is required before these can handle even a moderate range of industrial process conditions. The applications of neutral networks for microstructure evolution after huge data information storage received from industry rolling mill plant is one of the promising resolution of the problem.

Formation of ultrafine grained ferrite and of martensite or bainite – martensite in low carbon steel by heavy deformation in dual phase region followed by accelerated cooling was experimental laboratory and industrial tasks. The microstructural refinement supplies an alternative approach to improve the strength of low temperature ductility [17]. The deformation microstructure was analysed by optical and scanning electron microscopy. It has been demonstrated that the equiaxed ferritic microstructure with a grain size of around 2÷4 µm was obtained by the strain – induced austenite to ferrite transformation. However, the laboratory experiments show that the dual – phase ferrite – martensite microstructure was formed when specimens were cooled to temperature around 873 K at a cooling rate 50÷70K/s and then deformed with a reduction at least 50% followed by water quenching. During industrial processing of plates there were different types of structure formed depending on cooling rate starting from ferrite – pearlite to ferrite – bainite and martensite mixtures. So we have obtained mainly multi – phase microstructures. Thus into phase transformation models for low carbon microalloyed with niobium steels were included all possible transformations. They were described by paper by Kondek at all [4] and Lis at all [18÷21]. The numerical calculations of austenite – ferrite structure evolution during thermomechanical rolling by accelerated cooling using finite element method for thermomechanical behaviour of microalloyed Nb steel were performed on PC-Pentium IV, 2,2 MHz computer.

CONCLUSIONS

1. The ferrite – martensite microstructure with a grain size about 2÷4 μm has been obtained in Nb microalloyed during laboratory experiments.
2. The proposed model for structure evolution was verified in industrial rolling of heavy plates of 8÷12 mm in thickness.
3. It is difficult to avoid banded ferrite – martensite or ferrite – pearlite and bainite – martensite microstructures after rolling in $(\alpha+\gamma)$ temperature range but the coarse proeutectoid ferrite and Widmannstäten microstructure might be replaced by the equiaxed, ultrafine grained ferrite using heavy deformation processing.

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