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Kinetics of Austenite Transformation and Bainite Structure Formation during Strain-Heat Hardening of Low-Perlite Steel X70 (X65) (API 5L Gr X-60, API 5L Gr X-70) Plates for Gas Pipelines

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The kinetics of austenite transformation and bainite structure formation during controlled rolling and strain-heat hardening of plates for X70 (X65) (API 5L Gr X-60, API 5L Gr X-70) steel gas pipelines was investigated. We have determined the optimum cooling rates of plates and molibdenum concentration in low-perlite steel providing the necessary amount of bainite structure at strain-heat hardening of plate products on mill 3600.

Keywords: PLATE, CONTROLLED ROLLING, STRAIN-HEAT HARDENING, BAINITE STRUCTURE, CHEMICAL COMPOSITION, MOLIBDENUM, COOLING RATE, STRUCTURE FORMATION

Introduction

Current technologies of X65 (API 5L Gr X-70) and X70 (API 5L Gr X-60) steel plate production for gas pipelines provide application of controlled rolling and strain-heat hardening, i.e. combination of controlled rolling processes and accelerated cooling of plate products at various rates (V_{cool}).

Application of strain-heat hardening is the most expedient for 18 mm-thick plates made of steel grade X70 and above, as increase of cooling rate brakes the growth of ferrite grains and dispersion particles, which promotes decrease of interparticle distance and formation of austenite nonequilibrium decomposition products, mainly of bainite type (“needlelike ferrite”), which has a positive effect on properties [1]. The required combination of strength, plastic and viscous properties in X65 steel plates (σ_{UTS}=530-628 N/mm^2) is achieved due to ferrite grain refining typical for controlled rolling, and in X70 (σ_{UTS}=590-710 N/mm^2) also due to formation of required amount of bainite (15-20%) formed at the expense of accelerated cooling under strain-heat hardening and Mo microalloying of steel up to 0.3% [1, 2].

It is necessary to note that upon customer's request steel of X65 type also can contain Mo up to 0.35% (see TS 14-1-5385, Table 2, note 5), which is alogical at lower strength as compared to steel X70, especially when using strain-heat hardening technique. Thus, investigation of impact of cooling rate and Mo concentration on austenite decomposition, bainite structure formation in required amount and properties is urgent in order to optimize these factors under controlled rolling and strain-heat hardening of low-perlite X65 and X70 steel plates.

The task of the present research is to study austenite transformation and bainite structure formation in X65 and X70 steel plates containing Mo at the cooling rates corresponding to controlled rolling and strain-heat hardening.

Results and Discussion

Undercooled austenite transformation kinetics of steel X70 was investigated by means of analysis of plate products cooling rate and CCT diagrams obtained by reconstruction of isothermal diagrams into CCT ones with further phase-structure analysis [3]. Chemical composition of steel X70 for CCT diagram construction was determined after analysis of 345 industrial batches of rolled metal, as a result of which an average composition with respect to content of major (C, Mn, Si) and alloying elements was selected (**Table 1**).

Table 1. Chemical composition of steel X70 selected for CCT diagram construction

Concentration of elements, %													
C	Mn	Si	S	P	Cr	Ni	Cu	Al	Nb	N	V	Ti	Mo
0.07	1.63	0.22	0.005	0.01	0.011	0.011	0.013	0.008	0.052	0.008	0.072	0.010	0.228

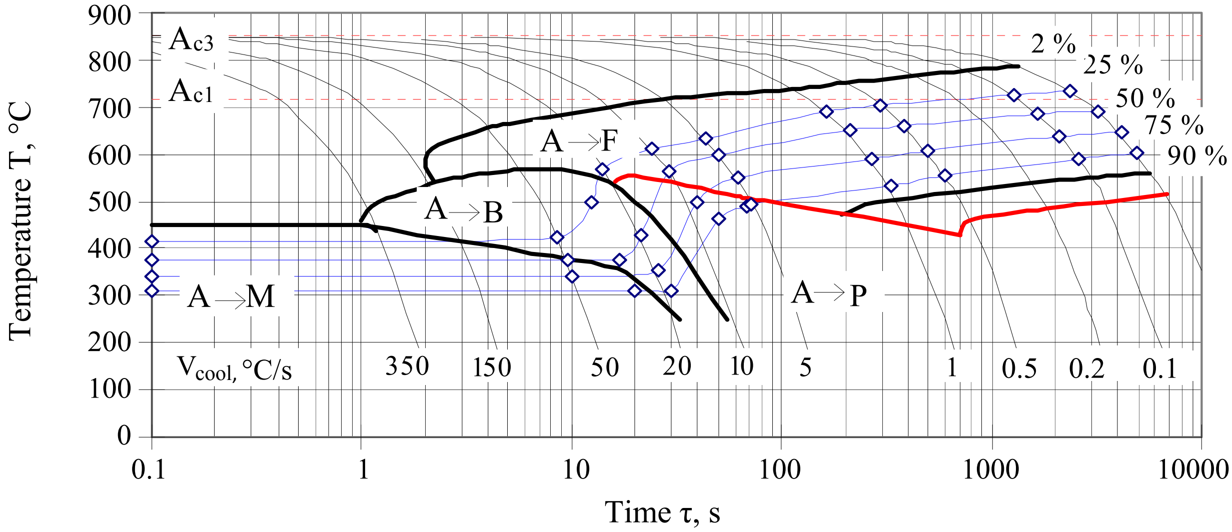

Figure 1. CCT diagram of steel X70 (X65) for the average chemical composition (Table 1): figures near cooling curves – V_{cool}(°C/s); figures near isoaustenitic curves (thin lines) – % of undercooled austenite decomposition; thick lines – boundaries of start (2%) and the end (99%) of precipitation areas of various structural constituents

It is necessary to notice that given average chemical composition also corresponds to steel X65, including with respect to Mo content as mentioned above, which allows using this CCT diagram (**Figure 1**) for austenite transformation analysis as applied to both specified steels.

Impact of cooling rate under controlled rolling and strain-heat hardening on the pattern of austenite decomposition kinetics was considered as applied to 18.7 mm-thick plates for manufacture of longitudinal tubes with diameter of 1420 mm. The analysis of given CCT diagram shows that steel X70 (X65) is characterized by a wide range of temperatures, in which austenite transformation is accompanied with bainite formation under continuous cooling. Enlarging the bainite area is caused by the presence of Mn, Ni, Nb, V and especially Mo (up to 0.228%) in steel, which coupled with raised cooling rates (≥10 °C/s) affects the formation of austenite nonequilibrium decomposition products of bainite type and insular martensite under strain-heat hardening [1].

Considering the change of cooling rates in the range 0.1-350 °C/s it is possible to define their impact on structure formation in various layers across the plate section from the surface layer ($V_{cool} \geq 350$ °C/s) to subsurface and central ones (V_{cool} = 50.0-0.1 °C/s) (**Figure 1**). The specified analysis points to possible heterogeneity of structure through-the-thickness of plate, especially under strain-heat hardening, however its negative effect on properties is not revealed, first of all, due to weak capacity for hardening of steels X70 (X65).

We will consider the effect of cooling rate in the range corresponding to controlled rolling (1-3 °C/s) and to plate accelerated cooling under strain-heat hardening (4-30 °C/s) on accelerated cooling plant of mill 3600. These ranges indicate the mass-averaged cooling rates of plates, which are determined in the process of pyrometrical measurements of temperature and used to control treatment process. Mainly ferrite-perlite structure across the plate section is characteristic for controlled rolling (V_{cool} = 1-3 °C/s). The area of austenite → perlite transformation is restricted by a narrow temperature range. When cooling plates up to 550-500 °C, austenite in amount up to 90% undergoes decomposition with the formation of fine-grained ferrite and 10% of perlite structure (**Figure 1**).

Application of plate accelerated cooling after controlled rolling, i.e. at higher cooling rates ($3 \leq V_{cool} \leq 10$ °C/s) can lead to the formation of pseudoeutectoid not identified in the diagram instead of perlite constituent.

In the process of strain-heat hardening of plates at the cooling rate $V_{cool} \geq 10$ °C/s, austenite decomposition of steel X70 (X65) according to CCT diagram (**Figure 1**) leads to formation of ferrite and bainite structures (the latter up to 20%) in the absence of perlite. However, when choosing strain-heat hardening conditions, the finishing temperature of austenite transformation should be above 450 °C, and maximum cooling rates should not exceed 15-20 °C/s, since at higher rates there is a probability of martensite formation instead of bainite structure and, as a result, decrease of plastic and viscous properties of plate products.

At chemical composition variation within the grade one, amount of bainite structure can differ from the specified level, and Mo among all elements has the most active impact on this process as construction of model CCT diagrams showed.

Connection between cooling rate of plates and amount of bainite structure in X70 (X65) steels of average chemical composition (**Table 1**) but variable (within selection) with respect to Mo concentration is presented in **Figure 2**.

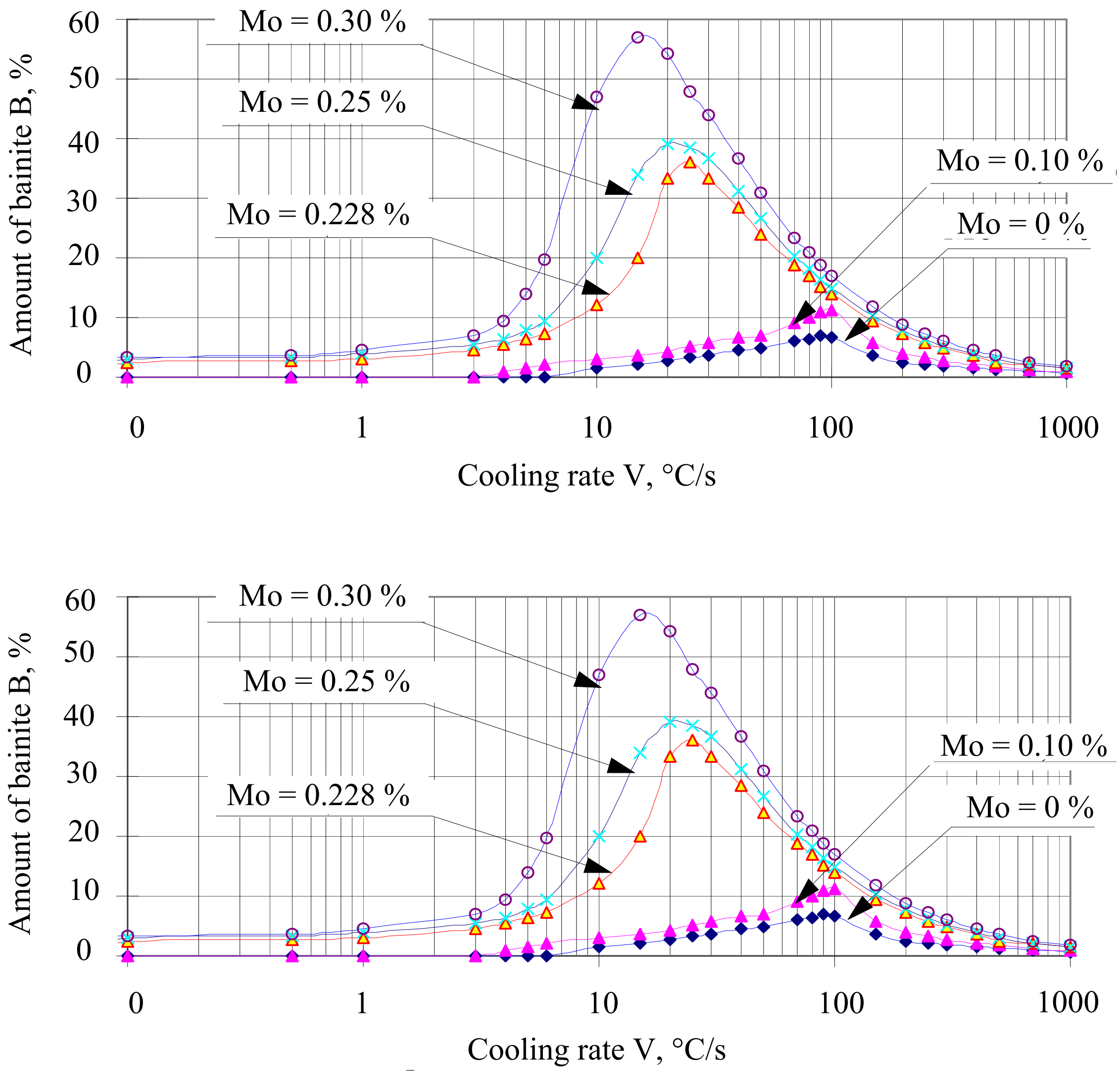

Figure 2. Change of bainite amount in X70(X65) steel microstructure depending on cooling rate and Mo content

It is clear from **Figure 1** that dependence of bainite amount on cooling rate V_{cool} has extremum character at all concentrations of Mo. And as Mo concentration in steel increases, the maximum moves toward slower cooling rates, and at the same time its value increases. For example, at Mo=0.1% and V_{cool}=100 °C/s, the maximum bainite amount in the microstructure can be only 10%, and at Mo=0.3% and V_{cool}=15 °C/s – 58%, i.e. Mo impact appears to be more effective than cooling rate. At the same time, range of cooling rates ensuring admissible amount of bainite in the structure (not more 15-20%) varies from 10-15 °C/s (at Mo=0.228%) to 5-6 °C/s (Mo=0.3%).

Given range of cooling rates was determined on ascending branches of dependence: %B=f (V_{cool}, Mo) (**Figure 2**), since the similar range defined on descending branch is wrong. At V_{cool}=60-100 °C/s and higher, the structure of ferrite-bainite matrix becomes mainly martensite.

Comparative analysis of effect of steel X70 (X65) chemical composition on bainite amount showed that it was possible to obtain bainite only up to 10% even at high cooling rates in the absence of Mo (**Figure 2**, a curve for Mo=0.0% at V_{cool}=100 °C/s), while in the presence of Mo and slower cooling rates – up to 40% of bainite (see a curve for Mo=0.25% at V_{cool}=20 °C/s).

It is also obvious that effective impact of Mo on bainite formation in steel X70 (X65) begins at Mo concentration more than 0.1%. In this conjunction, admissible higher concentration of Mo in steel X65 under controlled rolling (V_{cool}=1-3 °C/s) can lead to the formation of 10% bainite, which is not necessary in order to achieve the required strength level (σ_{UTS}=530-628 N/mm^2).

At the same time, at the maximum range of mass-averaged cooling rates V_{cool}=10-20 °C/s for 18-20 mm-thick plates, it is possible to obtain up to 45-55% of bainite in steel X70 (X65) at Mo concentration up to 0.3% (**Figure 2**). However, as austenite decomposition across the section of plate products takes place at cooling rate up to 10 °C/s, the required amount of bainite (15-20%) can be obtained at Mo content lowered to 0.25% as compared to the standard Mo content (0.3%) for steel X70.

Conclusions

1. Obtained results allow estimating effect of chemical composition and cooling rates of X65 and X70 steel plates for gas pipelines under controlled rolling and strain-deformation hardening in order to provide the required ratio of equilibrum (ferrite-perlite) and nonequilibrium (bainite-martensite) structures in plate products.
2. The defined correlation between plate cooling rates and Mo concentration in steels X65, X70 concerning the effect on bainite structure amount allows optimizing the content of this scarce element in the process of strain-deformation hardening.
3. Mo concentration in steel X65 up to 0.35% (upon customer's request) is not necessary for obtaining required structure and properties in plates of width up to 18.7 mm, and for X70 steel plates the maximum Mo content can be lowered down to 0.25% providing V_{cool}=10-20 °C/s, which is achieved when deformation-heat hardening.

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Исследование кинетики превращения аустенита и формирования бейнитной структуры при деформационно-термическом упрочнении листов из малоперлитной стали Х70(Х65) для труб газопроводов

Спиваков В. И., Орлов Э. А., Литвиненко П. Л., Ноговицын А. В.

Исследовали кинетику превращения аустенита и формирования бейнитной структуры при контролируемой прокатке и деформационно-термическом упрочнении (ДТУ) толстых листов для труб газопроводов из сталей категории прочности Х70(Х65). Установлены оптимальные скорости охлаждения листов и содержания молибдена в малоперлитной стали, обеспечивающие требуемый объем бейнитной структуры при ДТУ проката в условиях стана 3600.