SIMULATION OF MICROSTRUCTURE EVOLUTION DURING HOT ROLLING OF ROUND BARS FROM MICROALLOYED STEEL

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Abstract

The paper presents a modified microstructure evolution model that better considers the influence of strain induced precipitation (SIP) on static recrystallisation (SRX) kinetics. This is achieved by calculating the time for the 50 % softening $t_{0.5}$ (s) by static recrystallisation separately for the situation when it does not occur and separately when SIP occurs. This approach makes the resulting model more sensitive to grain coarsening in the high temperature rolling region, which is a consequence of the rapid progression of SRX and the larger interpass times during rolling on the country cross and continuous rolling mills. A method for deriving a modified model based on previously published two-stage softening curves is described. The modified model was used to design a rolling mode for a 90 mm diameter round bar. The modelling can be used to determine the necessary reduction in rolling temperature to induce SIP while the rolling is still in progress. This is because, during conventional rolling, SIP occurs after the last pass and thus has no effect on austenite grain size. Lowering the rolling temperature by 45 °C, it is possible to reduce the grain size from 80 to 45 μm while increasing the mean flow stress (MFS) by only 15 % in the 8th pass. The resulting grain size for both rolling regimes is consistent with the operating results. A second controlled rolling mode is also presented (reduction of the rolling temperature by 100 °C), which leads to a grain refinement to 25 μm, but at the cost of an increase in MFS of about 40 % in the 8th pass. The modified model can also be used to optimise the chemical composition of the steel.

Keywords: Metallurgy, steel, recrystallisation, precipitation, microstructure evolution

1. INTRODUCTION

1.1. Microstructure evolution model

Customer interest in higher strength steels and interest in reducing the cost of alloying elements leads to increased use of controlled forming processes in the production of long and flat products. However, this requires a detailed mapping of the structure-forming processes during the entire rolling process (heating, deformation-temperature history and cooling). One of the tools that metallurgists and researchers in steel mills can use are microstructure evolution models in the form of a spreadsheet, as introduced by JONAS [1-2]. The input variables of the model are the chemical composition of the steel (C, Mn, Si, Nb, V, Ti), the austenite grain size after heating, the temperature in each pass (which can be determined by operational measurement, analytical or numerical calculation or using FEM), the elongation coefficient for each pass (determined from calibration tables, by operational measurement of the dimensions of the rolls or numerical simulations), length of the interpass times (calculated from rolling speed and distance between rolls in the case of continuous mills, or by operational measurement or analysis of long-term operational data such as current consumption in the case of the country cross or reversible rolling mills). The model calculates the following input variables: the actual longitudinal strain, the mean strain rate and the Zener-Hollomon parameter. For its calculation, knowledge of the activation energy Q ($J \cdot mol^{-1}$) is required, which is either

determined by calculation based on the chemical composition of the steel or obtained from the literature for Nb microalloyed steels.

The output of the model is information about the strain induced precipitation, which is calculated based on these parameters:

- K_s - supersaturation ratio of steel concerning the heating temperature,
- t_{ps} (s) - time of the precipitation onset at a given temperature (calculated using the modified Dutta-Sellars model of Siciliano and Jonas [1-2] (with constants $A = 3 \cdot 10^{-6}$ and $B = 2.5 \cdot 10^{10}$. This modification considers the influence of Mn (increases the solubility of Nb in steel and thus delays precipitation) and Si (decreases the solubility of Nb in steel and thus accelerates precipitation),
- $\Sigma t_{ip}/t_{ps}$ - an indicator that successively adds the contributions of individual passes to reach the precipitation onset time (see **Figure 1**). If its value reaches 1, then precipitation has occurred.

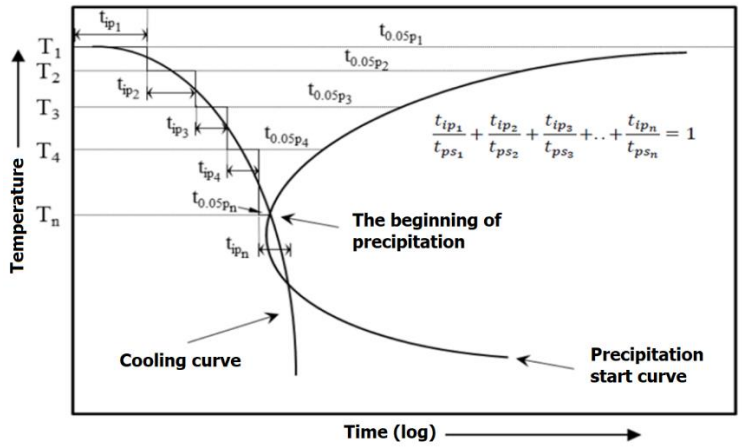

Figure 1 Illustration of the concept of successive contributions of individual passes (from 1 to n) to calculate the onset of precipitation

Information about the dynamic recrystallisation (DRX) process, which is calculated using the following parameters:

- e_a - cumulative strain. If complete softening from the previous pass has not been achieved by post-dynamic recrystallisation (MDRX - metadynamic recrystallisation or SRX - static recrystallisation), a proportional part of the strain (according to the value of the proportion of the fractional softening X) from the previous pass is added to the strain in the current pass,
- e_{cr} - critical strain for the initiation of DRX, which is calculated using the peak strain (it is a function of the Zener-Hollomon parameter) and considers the effect of the Nb equivalent,
- X_{DRX} - the proportion of fractional softening is calculated using the modified Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation, using the strain required to soften half of the structure $e_{0.5.}$
- Information about the progress of post-dynamic recrystallisation (SRX or MDRX), which is calculated using the following parameters:
- X_{MDRX} - the proportion of postdynamically recrystallised grain calculated using the Johnson (JMAK) equation using the time required for half of the structure to soften $t_{0.5}$ (s).
- $t_{0,5}$ (s) - the time needed for softening is calculated separately for SRX and MDRX (if DRX was started in the previous pass). Through this parameter, the precipitation model is linked to the recrystallisation and austenite grain size evolution model, where if precipitation has taken place, the value of $t_{0,5}$ (s) for both SRX and MDRX is multiplied by 10 (simulating the effect of precipitation on RX deceleration)

The grain size, as an input value for the following pass as a multiple choice.

- D_{RX} (μm) - the recrystallised grain size (SRX or MDRX). This value is never used for a further pass because only one of these variations can always occur:
  1) Recrystallisation is over - grain coarsening after SRX or MDRX counts,
  2) Recrystallisation is not complete - average grain size is calculated.
- D_{gg} (μm) - grain size after grain coarsening (grain growth) considers whether precipitation took place and the inhibiting effect of precipitates on the mobility of grain boundaries. If SIP did not occur, then equations are used for t_{ip} < 1 s and vice versa).
- Mean Flow Stress (MFS) according to Misaka and modified for microalloyed steels according to Siciliano and Jonas [1-2].

1.2. Microstructure model modification

A disadvantage of the model described in the previous section is the weak connection between precipitation and recrystallisation. The equation describes the kinetics of recrystallisation for calculating $t_{0.5}$ (s), e.g., for microalloyed Nb steels [3]:

$$t_{0,5}^{SRX} = (-5{,}24 + 550 \cdot [Nb]) \cdot 10^{-18} \cdot e^{(-4+77\cdot[Nb])} \cdot D_0^2 \cdot exp\left(\frac{330\,000}{R \cdot T}\right) \quad (1)$$

where $t_{0,5}^{SRX}$(s) is the time for the 50 % softening, e (-) is strain, D_0 (μm) is the austenite grain size, R (J·K^{-1}·mol^1 is the molar gas constant and T (°C) is temperature.

This equation is valid for both the situation when SIP has not occurred and the situation when SIP has occurred, automatically assuming that SIP will occur when the temperature drops below a certain value. Thus, it does not consider the full deformation-temperature history available in the form of the $\Sigma t_{ip}/t_{ps}$ parameter.

In the literature [4-10], we can encounter two-step curves describing the growth of the proportion of softened structure during the interpass time depending on the thermodynamic conditions of forming, i.e., temperature, strain, strain rate and grain size. The most complete data set represents the work of authors around Medina [11-16]. The data of these authors were used in the modification of our model. The two-stage curves presented in that literature (see **Figure 2**), or the original points, were divided into a part without SIP and a part with SIP and interleaved using Avrami S-curves (see **Figure 3**).

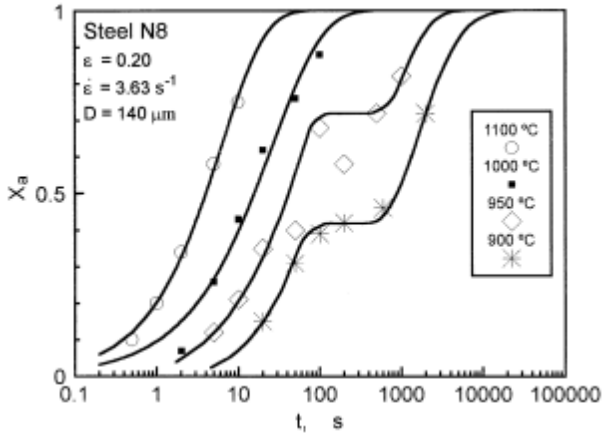

Figure 2 Variation in the fractional softening (X_a) with time (t) [14]

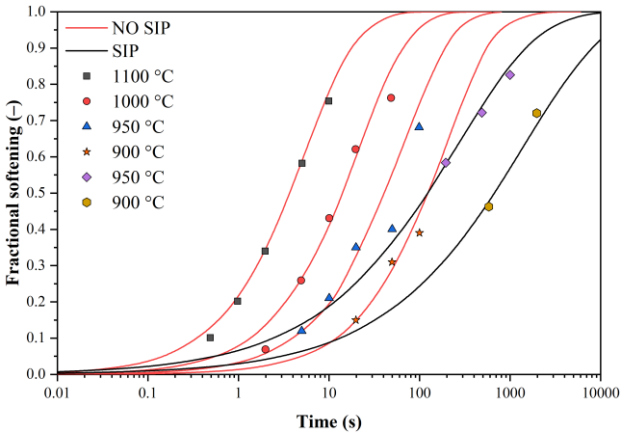

Figure 3 Plotting the experimental data with S-curves of original data see Figure 2

Using statistical analysis, the following equations were derived to describe $t_{0.5}$ (s):

Without SIP:

$$t_{0.5} = \exp\left(6.036 \cdot e - 80.87 \cdot \%Nb - 19.83\right) \cdot \exp\left(\frac{1\,089\,469 \cdot \%Nb - 121\,212 \cdot e + 248\,346}{R \cdot T}\right) \quad (2)$$

With SIP:

$$t_{0.5} = \exp\left(32.235 \cdot e - 329.6 \cdot \%Nb - 43.24\right) \cdot \exp\left(\frac{4\,184\,324 \cdot \%Nb - 416\,137 \cdot e + 496\,325}{R \cdot T}\right) \quad (3)$$

Since, in the experiment from which our data was taken, the grain size ranged from 140 to 210 μm, it was necessary to add a term to the equations to describe $t_{0.5}$ to account for the change in grain size during actual rolling.

$$t_{0.5(D)} = t_{0.5}\left(\frac{D_0}{\bar{D}}\right)^2 \quad (4)$$

where $\bar{D}$ is the average value of grain size used in the experiment (180 μm).

1.3. Comparison of the new equations with the original equations of other authors

We have compared our equations (2 to 4) with equation (1). The plots of the dependence of $t_{0.5}$ (s) on temperature for three different grain size values and for limiting values of Nb content and partial strain value are shown in **Figure 4**. We intended that the new equation for calculating $t_{0.5}$ (s) without SIP at higher temperatures should roughly match the equations from the literature. Conversely, the new equation for calculating $t_{0.5}$ with SIP should match the equations from the literature at lower temperatures (below the zero recrystallisation temperature of T_{NR} (°C)). As shown in **Figure 4**, similar values using our and equation (1) are obtained in a relatively narrow temperature range of about 900 and 975 °C, assuming that the conditions for initiating SIP are met. Suppose these conditions are not met (at any temperature). In that case, we obtain approximately one order of magnitude smaller values of $t_{0.5}$ (s) using the new equations, which will lead to the rapid completion of SRX and significant grain coarsening in the case of rolling with larger interpass times (reciprocating and continuous passes). This is consistent with our operational experience with rolling Nb microalloyed steel (see next section).

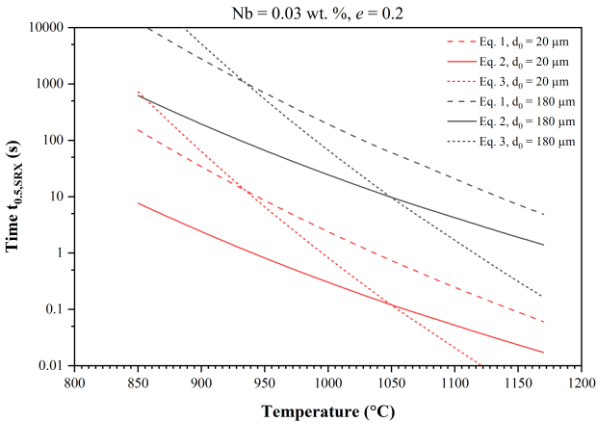

Figure 4 Comparison of $t_{0.5}$ (s) according to equations (1 to 3) and equation (4)

2. SIMULATION OF CONTROLLED FORMING USING A MODIFIED MODEL

The modified model described in the previous chapter can now simulate the microstructure evolution of other profiles of the same type of steel (Nb alloy steel, with a carbon content above 0,15 wt. %). The model for normal rolling or rolling with a temperature reduced by 100 °C of a 90 mm diameter round bar is shown in **Figures 5** and **6**. The input parameters were taken from the calibration table, and the temperatures were estimated based on experience with O100 (100 mm diameter round bar). The temperature reduction is achieved by free cooling the roll before the 6th stand. For a given temperature reduction, the delay time needs to be calculated (calculated with a cooling rate of 0.4 °C·s^{-1}). The calculated value is orange in the t_{ip} column (5th pass). To calculate the recrystallisation or coarsening of the grain after the last pass, the values of the time to the start of precipitation (orange cell in the t_{ip} (s) column of the 9th pass) and the temperature of the start of precipitation (orange cell in the T_i (°C) column) are used.

O90				2			K53M			13400k			LIBERTY
Nb	Mn	Si		C	A	Ti	T_{RH}	Nb_{eff}	e_{cr}/e_p	V	N	Q_{def}	
0,029	1,48	0,16		0,155	1,61E-05	0,001	1200	0,0184	0,60	0,001	0,0106	400 000	

Conventional rolling										Sum								
Pass	d	T_i	T_{ip}	e	t_{ip}	é	Z	K_s	t_{ps}	t_{ip}/t_{ps}	SIP?	e_a	e_{cr}	DRX?	$e_{0,5}$	X_{dyn}	$t_{0,5}$	X
	(μm)	(°C)	(°C)	(–)	(s)	(1/s)	(1/s)		(s)	(–)		(–)	(–)		(–)	(–)	(s)	(–)
0		1200								*0*								
1	250	1150	1135	0,086	10	2	9,62E+14	1,45	3E+28	0,00	no	0,09	0,83	no	0,43	0,00	7,42	0,537
2	184	1120	1110	0,223	10	2	1,99E+15	1,84	1E+11	0,00	no	0,26	0,81	no	0,44	0,00	2,75	0,874
3	121	1100	1090	0,095	11	2	3,29E+15	2,16	3E+07	0,00	no	0,13	0,71	no	0,42	0,00	3,05	0,872
4	136	1080	1061	0,215	13	2	5,53E+15	2,56	2E+05	0,00	no	0,23	0,82	no	0,47	0,00	3,87	0,853
5	96,5	1070	1049	0,174	15	2	7,20E+15	2,78	4E+04	0,00	no	0,21	0,73	no	0,44	0,00	2,70	0,958
6	102	1055	1034	0,077	13	2	1,08E+16	3,17	2E+04	0,00	no	0,09	0,80	no	0,47	0,00	7,37	0,634
7	98,5	1040	1035	0,140	13	2	1,63E+16	3,63	1E+03	0,01	no	0,17	0,84	no	0,50	0,00	4,33	0,819
8	86,8	1030	1020	0,451	24	4	4,32E+16	3,98	2E+02	0,14	no	0,48	0,93	no	0,52	0,00	0,87	1,000
9	63,4	1010	1002	0,182	31	8	1,54E+17	4,79	1E+02	0,40	no	0,18	0,99	no	0,53	0,00	3,12	0,997
F	79,2	994						5,57	Redundant strain for phase transformation						6E-04			

Figure 5 Print Screen of input parameters and outputs of the O90 microstructure development model - conventional (normal) rolling

O90				2			K53M			13400k			LIBERTY
Nb	Mn	Si		C	A	Ti	T_{RH}	Nb_{eff}	e_{cr}/e_p	V	N	Q_{def}	
0,029	1,48	0,16		0,155	1,61E-05	0,001	1200	0,0184	0,60	0,001	0,0106	400 000	

Variant 3 (−100°C)										Sum								
Pass	d	T_i	T_{ip}	e	t_{ip}	é	Z	K_s	t_{ps}	t_{ip}/t_{ps}	SIP?	e_a	e_{cr}	DRX?	$e_{0,5}$	X_{dyn}	$t_{0,5}$	X
	(μm)	(°C)	(°C)	(–)	(s)	(1/s)	(1/s)		(s)	(–)		(–)	(–)		(–)	(–)	(s)	(–)
0		1200								*0*								
1	250	1150	1135	0,086	10	2	9,62E+14	1,45	3E+28	0,00	no	0,09	0,83	no	0,43	0,00	7,42	0,54
2	184	1120	1110	0,223	10	2	1,99E+15	1,84	1E+11	0,00	no	0,26	0,81	no	0,44	0,00	2,75	0,87
3	121	1100	1090	0,095	11	2	3,29E+15	2,16	3E+07	0,00	no	0,13	0,71	no	0,42	0,00	3,05	0,87
4	136	1080	1075	0,215	13	2	5,53E+15	2,56	1E+05	0,00	no	0,23	0,82	no	0,47	0,00	3,07	0,91
5	108	1070	1013	0,174	265	2	7,20E+15	2,78	2E+05	0,00	no	0,19	0,77	no	0,45	0,00	6,92	1,00
6	101	955	948	0,077	13	2	2,06E+17	8,26	1E+02	0,11	no	0,08	1,31	no	0,70	0,00	43,87	0,16
7	82,3	940	935	0,140	13	2	3,35E+17	9,66	3E+01	0,48	no	0,20	1,29	no	0,71	0,00	17,75	0,34
8	51,4	930	920	0,451	24	4	9,30E+17	10,75	9E+00	3,19	yes	0,59	1,21	no	0,68	0,00	20,27	0,79
9	24,6	910	910	0,182	0	8	3,66E+18	13,38	8E+00	3,19	yes	0,30	1,06	no	0,64	0,00	47,12	0,00
F	24,6	910						13,38	Redundant strain for phase transformation						0,303			

Figure 6 Print Screen of input parameters and outputs of the O90 microstructure development model - controlled rolling (ΔT = 100 °C)

The graphs illustrate the model's outputs in **Figures 7** and **8**. **Figure 7** shows a plot of grain size evolution for all three variants. In the conventional rolling, SRX takes place after each pass (only partially after the 6th pass, X = 0.63). Thus, the grain refines to 63 μm before the 9th pass, but then, due to the relatively small deformation in the last pass and the slow onset of SIP after rolling, the grain coarsens to 79 μm. By lowering the temperature before the 6th stand by 45 °C, precipitation can be induced in the 8th pass, which ultimately results in a refinement of the austenitic grain to 45 μm before phase transformation. In addition, a residual strain of 0.18 results in a refinement of the ferritic grain. This is already a significant improvement since, in austenitic grains of this size, the formation of Widmannstatten ferrite, which can cause low impact work of rolled bars, can no longer be expected. Lowering the temperature before the 6th stand by 100 °C leads to only a partial SRX in the 6th to 8th pass, which, together with the SIP in the 8th pass, leads to a grain refinement down to 25 μm. Combined with a residual strain of 0.3, we can expect a ferritic grain below 20 μm, which is already close to the structure after normalisation annealing (from previous measurements, we have determined 11 - 16 μm after normalisation annealing for this steel).

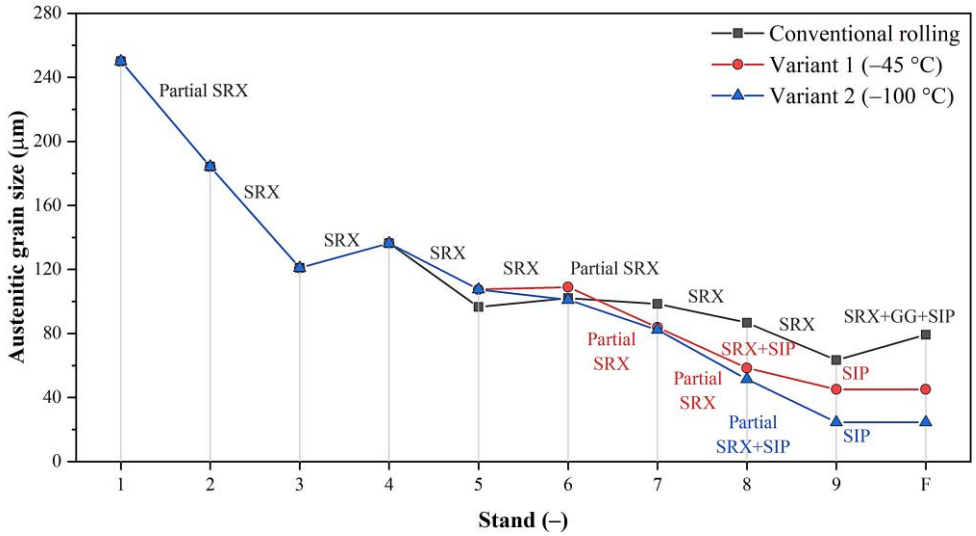

Figure 7 Grain size evolution during O90 rolling on individual stands (K52M, all variants considered)

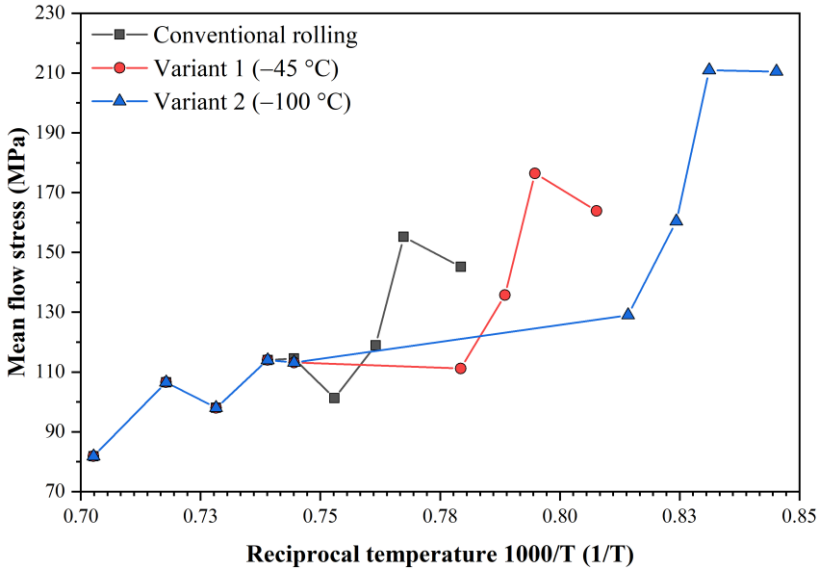

Figure 8 Dependence of MFS on reciprocal temperature (O90, all variants)

CONCLUSION

This paper presented a modified model of microstructure evolution that better considers the effect of SIP on SRX kinetics, in contrast to the existing model. This model is particularly suitable for rolling with larger interpass times during high temperature passes, as it better explains the causes of the enormous austenitic grain coarsening encountered during actual rolling at the Heavy Section Mill at Liberty Ostrava a.s.

The rolling of a 90 mm diameter round bar was simulated using the modified model. Firstly, conventional rolling was modelled, where it was shown that SIP takes place after the last pass and does not have such a positive effect on grain refinement, the predicted grain size is about 80 µm, which corresponds very well to the operational results. Using the modified model, a rolling mode was designed to cause the SIP to take place after the 8th pass. The temperature needs to be reduced by 45 °C before the 6th pass. The SIP after the 8th pass results in refinement of the austenitic grain to 45 µm. This value is also very close to the operating results in controlled rolling. However, this mode will require an increase in the MFS in the 8th pass of about 15 %. When designing the next controlled rolling mode, it is logical to look for a temperature

reduction that will induce SIP already in the 7th pass. However, this is not possible with the given rolling mode because too large a temperature drop together with a small total strain in the previous passes would lead to a situation where no SIP occurs at all. Therefore, we have settled for a regime where SRX is suppressed in the last passes (6 to 8) and, thus, due to the SIP after the 8th pass. We obtain an austenitic grain after rolling with a size of 25 μm. This mode has not yet been operationally verified because there is concern that increasing the MFS in the 8th pass by about 40 % could damage the rolling stands or rolls.

This case study was used to show how a modified development model can be used to design the rolling mode. However, due to its sensitivity to chemical composition, this model can also be used to modify the chemical composition of the steel. It is possible to find contents of Nb, Si (supports SIP by reducing the solubility of Nb in the Fe matrix) and Mn (opposite effect to Si), for which the required temperature reduction to induce SIP while still rolling will be minimal.

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