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INFLUENCE OF SELECTED PARAMETERS OF THE THERMOMECHANICAL ROLLING PROCESS OF HSLA STEEL ON THE TRANSFORMATION OF AUSTENITE INTO FERRITE

The study analyzed two selected representative HSLA steels rolled at the Krakow branch of ArcelorMittal Poland S.A. The aim of the analysis was to determine the effect of parameters such as strain and cooling rate on the onset temperature of the transformation from austenite to ferrite. Dilatometric tests were carried out, followed by strain dilatometry. The cooling rate was varied and its relationship with the temperature of the beginning of austenite to ferrite transformation (Ar_3) was determined. In the second part of the study, the subject literature was analyzed to find out how quickly the Ar_3 temperature could be calculated. The available equations for calculating the Ar_3 temperature were checked. However, the results of the calculations were not consistent enough to use these equations in the actual process. Therefore, the authors decided to develop their own equation – the proposed solution allows the calculation of the Ar_3 temperature for the two selected HSLA steels mentioned above with an accuracy of several degrees and a correlation of more than 90%.

Keywords: HSLA steel; thermomechanical rolling; dilatometry tests; Ar_3 temperature calculation; austenite to ferrite transformation

1. Introduction

High-strength low-alloy steels (HSLA) are steels containing Nb, Ti and V micro-additives. These steels are produced by thermo-mechanical rolling – in Poland, the only place where they can be produced on a mass scale is the Krakow Hot Rolling Mill of ArcelorMittal Poland S.A. During thermo-mechanical rolling, it is particularly important to know the temperatures at the end of the deformation. The final passes are carried out at the temperatures below the recrystallisation stop temperature (RST), but at the same time at the temperatures high enough to continue rolling in the austenitic range – so that the rolling forces are as low as possible due to the profitable microstructure [1]. In this respect, the knowledge of Ar_3 temperature, i.e. the temperature of the beginning of the transformation from austenite to ferrite, is extremely important. The window between the end-rolling temperature and the Ar_3 temperature can be very narrow in the industrial process [2]. The classic method of calculating the Ar_3 temperature is dilatometry [3]. However, this involves performing the tests that take some time and costs. There is a number of equations in the literature that can be used to calculate the Ar_3 temperature [4]. However, as the authors point out, not every equation will be suitable for a particular grade of steel. In the work presented below, the authors carried out dilatometric analyses of the investigated steels and then checked the applicability of the equations to the industrial process.

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2. Materials and methods

Two representative grades of HSLA steels, rolled at the Kraków branch of ArcelorMittal Poland S.A., were selected for the study. The chemical composition of the steels studied is shown in TABLE 1. The steel grades have been given the working names S1 and S2, with S1 steel being Nb micro-alloyed steel and S2 steel with Nb + Ti micro-alloying elements.

TABLE 1

The chemical composition of the investigated steels

Steel	C_{avg}, wt.%	Mn_{avg}, wt.%	Nb_{avg}, wt.%	Ti_{avg}, wt.%	V_{avg}, wt.%
S1	<0.07	<0.90	<0.04	<0.01	<0.01
S2	<0.08	<1.00	<0.06	<0.04	<0.01

Six cylindrical specimens (3 mm in diameter and 10 mm in height) were prepared from each investigated steel. The specimens were tested on a Bahr DIL 850 dilatometer. Specimens marked 1 and 7 were subjected to deformation-free dilatometry according to the following scheme: heating up to the temperature of 1250°C, holding at this temperature for 5 minutes and then cooling with the cooling rate of 0.5 K/s. The samples marked 2 to 6 and 8 to 12 were subjected to deformation dilatometry. The samples were austenitized for 5 minutes at the temperature of 1250°C, then cooled with the cooling rate of 1 K/s to the temperature of 1100°C, and then deformed (35% reduction of sample height). This was followed by a further cooling at a cooling rate of 1 K/s to the temperature of 890°C (i.e. below the recrystallisation stop temperature for the steels tested), where a second deformation (further 10% reduction of sample height) occurred. Then the selected samples were cooled at a varying cooling rate of 0.5, 10, 25, 40 and 60 K/s.

The second part of the study involved a literature analysis of the availability of equations for calculating Ar_3 temperature. Many equations are described in detail in the publications. A selection was made – rejecting equations without the influence of the cooling rate – as dilatometric tests showed a clear influence of the cooling rate on the Ar_3 temperature shift. The following equations were checked for applicability to the analysis of the steels under investigation:

$$Ar_3 = 903 - 328C - 102Mn + 116Nb - 0.909CR \quad [5]\ (1)$$

$$Ar_3 = 925.95 - 494.74C - 64.8Mn - 10CR^{0.5} \quad [6]\ (2)$$

$$Ar_3 = 892.15 - 523.35C + 86.50Si - 65.88Mn - 46.85Cr + 21.82Mo - 45.17Ni + 405.05C^2 - 180.54CSi - 3.65CMn + 92.20CCr - 69.66CMo + 37.50CNi + 2.43GS - 5.18\sqrt{CR} - 6.78\ln(CR) \quad [7]\ (3)$$

$$Ar_3 = 833.6 - 190.6C - 67.4Mn + 1522S - 2296\left(N - \frac{Ti}{3.5}\right) - 1532Nb + 7.91d^{-\frac{1}{2}} - 0.117CR \quad [8]\ (4)$$

$$Ar_3 = 868 - 181C - 75.8Mn + 1086S - 3799\left(N - \frac{Ti}{3.5}\right) - 1767Nb - 0.0933CR \quad [8]\ (5)$$

$$Ar_3 = 862 - 182C - 76.1Mn + 1121S - 1804Nb + 1168Ti - 2852N - 0.0084CR \quad [8]\ (6)$$

$$Ar_3 = 874.44 - 512.0465C - 40.915Mn + 23.075Si + 567.126C^2 - 199.551CMn + 265.797CSi - 8.296\ln\left(\frac{0.002d_\gamma}{\ln(2)}\right) - 1.03\sqrt{CR} - 11.334\ln(CR) \quad [9]\ (7)$$

$$Ar_3 = 811 - 255C - 7Mn + 19Si - 19CR^{0.481} - 0.5e^{\left(\frac{0.042d_\gamma + 7.8}{2.7402}\right)} \quad [10]\ (8)$$

$$Ar_3 = 857 - 257C - 69Mn + 23Si - 38Ni - 20Cr - 20Mo + 34V + 26Cu + 0.07T_A - 17CR^{0.25} \quad [11]\ (9)$$

$$Ar_3 = 1.375\begin{pmatrix} 937.3 - 224.5\sqrt{C} - \\ 17Mn + 34Si - 14Ni + \\ 21.6Mo + 41.8V - 20Cu \end{pmatrix} - 2.3CR - 339 \quad [12]\ (10)$$

$$Ar_3 = 370\exp\left(-\frac{\sqrt{d_\gamma}}{6.7}\right) - 325CR^{0.1} - 5649Nb + 78194Nb^2 + 1019 \quad [13]\ (11)$$

$$Ar_3 = 914 - 6.85CR - 650C - 134Mn + 179Si \quad [14]\ (12)$$

Where: C, Mn, Nb, Si, Cr, Mo, Ni, Ti, V, Cu are the chemical elements contents in weight %, CR – cooling rate in K/s, GS – austenite grain size in ASTM units, d – austenite grain size in mm, d_γ – austenite grain size in μm, T_A – austenitizing temperature in °C.

3. Results and discussion

Fig. 1 shows the dilatometric curves obtained for the samples tested without deformation for samples 1 and 7, together with the samples microstructures. The cooling rate for the experiment was set so as to obtain a ferritic-pearlitic microstructure, which, as can be seen from the attached photographs of the microstructure, was successful. TABLE 2 shows the full results of the dilatometric test.

TABLE 2

Dilatometric tests results

Sample code	Cooling rate, K/s	Ar_1, °C	Ar_3, °C
1	0.5	625	795
2	0.5	600	815
3	10	570	730
4	25	510	720
5	40	500	705
6	60	495	680
7	0.5	640	770
8	0.5	620	830
9	10	520	700
10	25	510	670
11	40	505	660
12	60	500	655

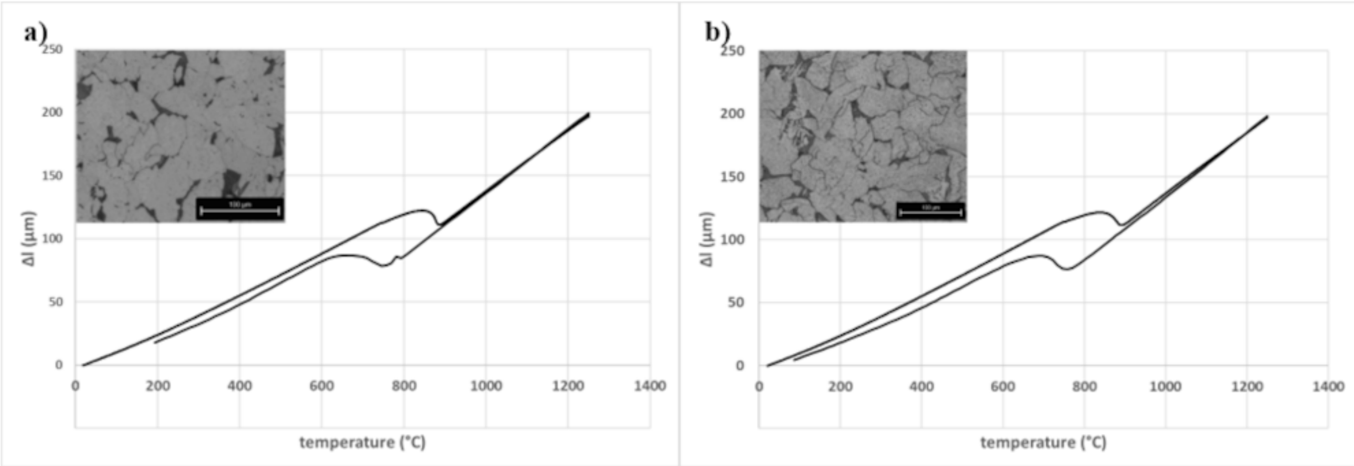

Fig. 1. The dilatometric curves with the microstructures of tested samples for: a) sample 1 – steel S1, b) sample 7 – steel S2

As can be seen from the study, both strain and cooling rate have a considerable influence on the temperature of the transformation of austenite to ferrite.

The application of strain at a level comparable to industrial conditions while maintaining the same cooling rate (samples 2 and 8) raised the temperature of the start of the transformation of austenite to ferrite in S1 steel by 20°C and in S2 steel by 60°C, respectively. The Ar_1 temperatures, which were not directly targeted by the tests, also changed – they were lowered in both cases by 25°C and 20°C, respectively. Thus, the application of deformation to the material intended for thermo-mechanical rolling considerably expands the austenite to ferrite transformation field, raising the temperature of transformation start. Subsequent tests (samples 3 to 6 and 9 to 12) were carried out with increasing cooling rates. The results show that Ar_3 temperature decreases with increasing cooling rate. The relationship in both cases is non-linear.

In the second part of the study equations 1 to 12 were checked. These equations, taken from the research works available in the technical literature, were developed to calculate the Ar_3 temperature for HSLA or similar steels. TABLE 3 and TABLE 4 show the results of the calculations performed using the above equations.

As can be seen, unfortunately none of the equations produced results at a reasonably good level. The linear-dependent equations on the cooling rate gave good results only for very low cooling rate or very high cooling rate, while the non-linear-dependent equations did not have a good enough fit. Some calculations were inaccurate by up to approx. 200°C, so it was decided to develop our own equation to calculate the Ar_3 temperature for HSLA steel rolled in Krakow. It was noted (Fig. 2) that the Ar_3 temperature dependence for both steels is logarithmic.

The relationship for both steels takes the form ln(CR) + H, where CR is the cooling rate and H is a certain value derived from the varying chemical composition. On this basis, the equation (13) was developed. The TABLE 5 shows a comparison between the experimental results and the results calculated

TABLE 3

Calculated Ar_3 temperatures using the equations 1 to 6

No of equation	1					2					3					4					5					6				
Cooling rate, K/s	0.5	10	25	40	60	0.5	10	25	40	60	0.5	10	25	40	60	0.5	10	25	40	60	0.5	10	25	40	60	0.5	10	25	40	60
Ar_3, °C – calculated steel S1	794	785	771	758	740	827	802	784	771	756	804	771	755	745	735	707	706	704	703	700	694	693	692	690	688	694	693	692	692	692
Ar_3, °C – from test steel S1	815	730	720	705	680	815	730	720	705	680	815	730	720	705	680	815	730	720	705	680	815	730	720	705	680	815	730	720	705	680
ΔT, °C	21	–55	–51	–53	–60	–12	–72	–64	–66	–76	11	–41	–35	–40	–55	108	24	16	2	–20	121	37	28	15	–8	121	37	28	13	–12
Ar_3, °C – calculated steel S2	788	779	766	752	734	821	796	778	765	751	798	765	750	740	729	712	711	710	708	705	710	709	708	706	704	703	699	699	699	699
Ar_3, °C – from test steel S2	830	700	670	660	655	830	700	670	660	655	830	700	670	660	655	830	700	670	660	655	830	700	670	660	655	830	700	670	660	655
ΔT, °C	42	–79	–96	–92	–79	9	–96	–108	–105	–96	32	–65	–80	–80	–74	118	–11	–40	–48	–50	120	–9	–38	–46	–49	127	1	–29	–39	–44

TABLE 4

Calculated Ar_3 temperatures using the equations 7 to 12

No of equation	7					8				
Cooling rate, K/s	0.5	10	25	40	60	0.5	10	25	40	60
Ar_3, °C – calculated for steel S1	807	771	759	752	746	688	644	612	589	565
Ar_3, °C – from test steel S1	815	730	720	705	680	815	730	720	705	680
ΔT, °C	8	–41	–39	–47	–66	127	86	108	116	115
Ar_3, °C – calculated for steel S2	802	765	753	746	740	686	642	610	588	564
Ar_3, °C – from test steel S2	830	700	670	660	655	830	700	670	660	655
ΔT, °C	28	–65	–83	–86	–85	144	58	60	72	91

No of equation	9					10				
Cooling rate, K/s	0.5	10	25	40	60	0.5	10	25	40	60
Ar_3, °C – calculated for steel S1	851	835	827	822	818	846	824	790	755	709
Ar_3, °C – from test steel S1	815	730	720	705	680	815	730	720	705	680
ΔT, °C	–36	–105	–107	–117	–138	–31	–94	–70	–50	–29
Ar_3, °C – calculated for steel S2	846	830	822	818	813	842	821	786	752	706
Ar_3, °C – from test steel S2	830	700	670	660	655	830	700	670	660	655
ΔT, °C	–16	–130	–152	–158	–158	–12	–121	–116	–92	–51

No of equation	11					12				
Cooling rate, K/s	0.5	10	25	40	60	0.5	10	25	40	60
Ar_3, °C – calculated for steel S1	674	568	529	508	488	749	683	581	478	341
Ar_3, °C – from test steel S1	815	730	720	705	680	815	730	720	705	680
ΔT, °C	141	162	191	197	192	66	47	139	227	339
Ar_3, °C – calculated for steel S2	688	582	543	522	502	739	674	571	468	331
Ar_3, °C – from test steel S2	830	700	670	660	655	830	700	670	660	655
ΔT, °C	142	118	127	138	153	91	26	99	192	324

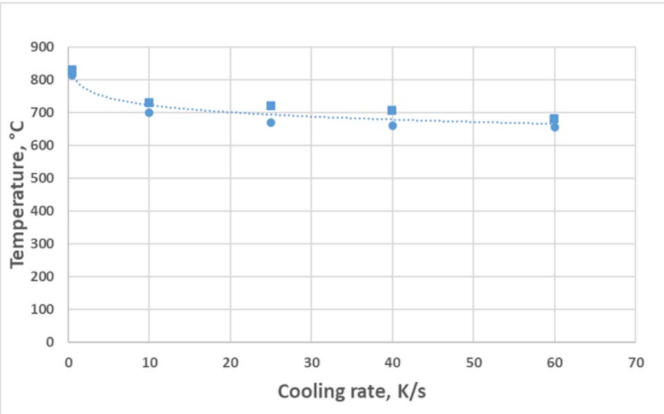

Fig. 2. Ar_3 temperatures from experiment for both steels – square points steel S1, dotted points steel S2

with the proposed new equation. The data correlation for both analyzed steels exceeded 90%.

$$Ar_3 = 832 - 200C - 30Mn + 75Si + 100Nb - 32\ln(CR) \quad (13)$$

Where: C, Mn, Si, Nb are alloy chemical elements contents in weight %, CR – cooling rate in K/s.

4. Conclusions

Knowledge of the Ar_3 temperature is extremely important for the correct design of thermo-mechanical rolling of HSLA steels. The following conclusions can be drawn from the research carried out:

- deformation of HSLA steel raises the Ar_3 temperature;
- the cooling rate has a significant effect on the onset of the transformation from austenite to ferrite, with increasing cooling rate the Ar_3 temperature decreases;
- at this stage of the research the obtained data allow to state, that the relationship between cooling rate and Ar_3 temperature for the steels studied is logarithmic. Further research will be carried out to make this correlation more and more precise;
- the equations available in the literature for calculating the Ar_3 temperature give large differences for the steels studied;
- the equation developed allows rapid and reasonably accurate calculation of the Ar_3 temperature for HSLA steels rolled in Krakow – data consistency is 90%;
- the development of the equation allows a quick estimation of the temperature of the beginning of the transformation of austenite to ferrite, and could be implemented even directly into the production cycle.

TABLE 5

Calculated Ar_3 temperatures using new equation

Cooling rate, K/s	Ar_3, °C – calculated for steel S1	Ar_3, °C – from test for steel S1	ΔT, °C	Ar_3, °C – calculated for steel S2	Ar_3, °C – from test for steel S2	ΔT, °C
0.5	819	815	4	817	830	–13
10	723	730	–7	721	700	21
25	693	720	–27	692	670	22
40	678	705	–27	677	660	17
60	665	680	–15	664	655	9

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