MICROSTRUCTURE EVOLUTION AND MECHANICAL PROPERTIES OF HOT ROLLED DUAL-PHASE STEEL

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Abstract

The influence of continuous mill 2000 hot rolling parameters on the high strength dual-phase (DP) steel with experimental chemical composition structure evolution was investigated. In order to obtain dual-phase microstructure modern computer and physical simulation methods are used during development of hot rolling schedules. Computer simulation of structure and mechanical properties formation was realized with the help of Hot Strip Mill Model (HSMM), ThermoCalc and AusEvol+ programs. Physical simulation of metal thermomechanical treatment was made by Gleeble-3800 using «tension-compression» technique. Varying the thermomechanical treatment parameters the ferrite-martensitic (FM) dual-phase steels of DP780-DP1180 strength class are received.

Keywords: Dual-phase steel, hot rolling, physical simulation, microstructure evolution, mechanical properties

1. INTRODUCTION

It was reported earlier [1] that it is possible to produce DP-1000 steels by means of hot rolling and subsequent thermo treatment and to receive microstructure and mechanical properties of these steels close to classical DP-steels produced by means of intercritical annealing after cold rolling. Recent research [1] was done for standard chemical composition DP-1000 steel and present research concerns high-strength dual-phase steel with experimental chemical composition.

DP-steels for stamping are basically produced by means of continuous hot rolling. The hot rolled DP-steels production scheme is presented on **Fig. 1**.

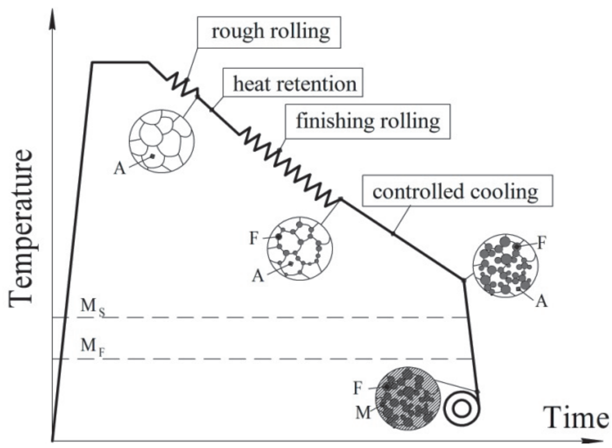

Fig. 1 The hot rolled DP-steels production scheme (A - austenite; F - ferrite; M - martensite; M_S - martensite start temperature; M_F - martensite finish temperature)

The purpose of present research is to determine the influence of hot continuous rolling parameters on structure and mechanical properties behavior of high strength DP-steels with experimental chemical composition.

2. EXPERIMENTAL PROCEDURE

The chemical composition of steel used in this study is presented in **Table 1**. The equilibrium transformation points of researched steel calculated in program *ThermoCalc* are the next: A_{e3}=795 °C, A_{e1}=700 °C.

Table 1 Chemical composition of steel used in this study

Elements	C	Si	Mn	Cr	Ni	Mo	Ti	Nb	V
Mass., %	0,16	0,5	1,34	0,04	0,3	0,2	0,004	0,03	0,03

For steel structure evolution and mechanical properties simulation next computer software was used:

- Universal program ***HSMM (Hot Strip Mill Model, INTEG* process group, inc.*)*** program simulates strip rolling process on continuous and reversing hot rolling mills; it provides thermal and deformational calculations during strip rolling from furnaces trough all process to controlled cooling. Computer simulation of hot rolling on continuous rolling mill 2000 was made based on existing virtual mill model developed in program *HSMM*.
- The ***ThermoCalc*** program was used for thermodynamic calculations and for multi-components systems diagram developing, the thermodynamic data base provides all calculations;
- The ***AusEvol+*** program simulates different processes in austenite such as grain growth, thermal relaxation, dynamic and static recrystallization [2], flow stress curves, the level of retained strain and also precipitation according to treatment parameters and chemical composition;

The physical simulation of metal thermomechanical treatment was made with the help of *Gleeble-3800*. The rolling mill 2000 scheme is presented on **Fig. 2**.

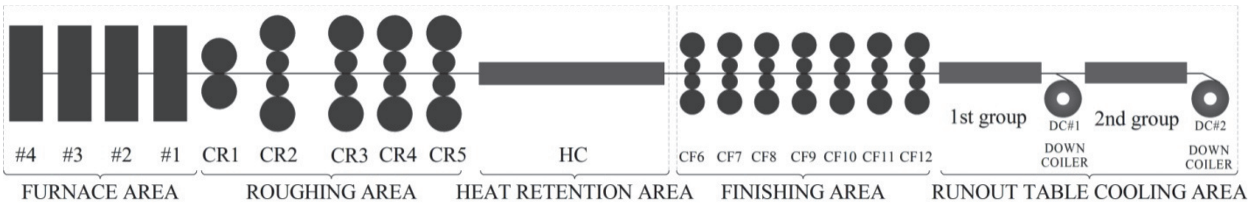

Fig. 2 The rolling mill 2000 scheme

The main tasks for different stages of hot rolling simulation are listed below:

Furnace and roughing areas:

1. To set reheat temperature in furnaces equal to 1200 °C in order to have Nb(CN) fully saluted;
2. To set maximum reductions in mills according to equipment characteristics;
3. To set rolling speed in order to have temperature at the end of roughing rolling equal to temperature of NbC precipitation;

Heat retention area (HRA):

1. To determine holding time for full NbC precipitation;
2. To set minimum delay time to uniform strip head, middle and tail temperature during finishing rolling (ΔT<30 °C);
3. To reach required temperature of finishing rolling beginning;

Finishing and runout table cooling areas (RTCA):

1. To set maximum reductions in mills according to equipment characteristics and obtained final strip thickness less than 3 mm;
2. To accumulate retained strain before phase transformation;
3. To set rolling speed in order to have temperature at the end of finishing rolling equal to temperature of deformation induced $\gamma \rightarrow \alpha$ transformation;
4. To hold strip at temperature of dual-phase region in order to reach full $\gamma \rightarrow \alpha$ transformation and to enrich austenite by carbon;
5. To cool strip in order to get required ferrite volume fraction and final ferrite-martensite (FM) structure.

3. COMPUTER SIMULATION OF HOT ROLLING

Hot rolling simulation was produced by means of *HSMM* program and microstructure evolution simulation during rolling by means of *AusEvol+* program. The base grade HSLA Nb/V/Ti was chosen for hot rolling on mill 2000 simulation in *HSMM* program. The initial dimensions of slab were: thickness of 150 mm, 8000 mm length and 1450 mm width.

In accordance with requirements listed above rolling schedule for roughing area (**Table 2**) was developed:

Table 2 The calculation results made by *HSMM* program for roughing area

Initial Data	Furnace	Stand CR1	Stand CR2	Stand CR3	Stand CR4	Stand CR5	HC (entrance)	HC (exit)
h, mm	150	108	60	35	21	13	13	13
ε	-	0,35	0,59	0,55	0,52	0,49	-	-
$\dot{\varepsilon}$, s^{-1}	-	2	4	5	10	20	-	-
Temperature, °C	1178	1126	1111	1090	1075	1060	1000	824

The calculation results of austenite grain size and concentration of Nb in solid solution during roughing rolling and holding time made by *AusEvol+* program for rolling schedule shown in **Table 2** are presented on **Fig. 3**. We can clearly see that austenite grain size decreases after each rolling pass according to static recrystallization and then increases. At the temperature of 1063 °C concentration of Nb monotonic decreases according to Nb(CN) precipitation induced by deformation. These precipitates of Nb(CN) at heat retention area block austenite grain growth.

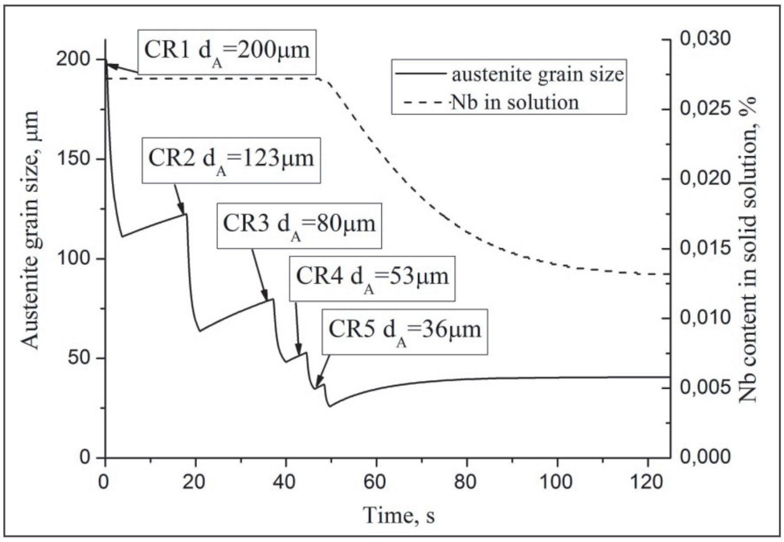

Fig. 3 The calculation results of austenite grain size and concentration of Nb in solid solution

In accordance with requirements listed above two rolling schedules for finishing area (**Table 3**) were developed, schedule 1 with rolling finishing temperature approximately equal to A_{e3} and schedule 2 with rolling finishing temperature approximately equal to A_{e1}.

Table 3 The calculation results made by *HSMM* program for finishing area

Initial Data	Stand CR6	Stand CR7	Stand CR8	Stand CR9	Stand CR10	Stand CR11	Stand CR12
Schedule 1							
ε	0,31	0,27	0,27	0,23	0,20	0,15	0,07
$\dot{\varepsilon}$, s^{-1}	20	29	43	57	73	81	64
Temperature, °C	824	817	810	804	795	788	778
Schedule 2							
ε	0,31	0,25	0,23	0,18	0,15	0,08	0,04
$\dot{\varepsilon}$, s^{-1}	20	27	37	44	51	44	32
Temperature, °C	810	793	776	760	742	724	700

4. PHYSICAL SIMULATION OF HOT ROLLING

Rolling schedules developed by *HSMM* program (**Table 2** and **Table 3**) were realized on *Gleeble-3800* system using "tension-compression" techniques described in details in [3]. The experiments scheme is shown on **Fig. 4**. The main purposes of present experiments are:

- **Schedule 0:** to determine average austenite grain size after roughing rolling and heat retention area;
- **Schedules 1 and 2:** to realize schedules 1 and 2 according to the Tables II and III and to cool specimens down with cooling speed of 50 °C/s in order to get ferrite-bainite microstructure;
- **Schedules 1a and 2a:** to realize schedules 1 and 2 according to the Tables II and III and to hold specimens at the rolling finishing temperature for 500 s in order to have maximum ferrite volume fraction; after that to cool specimens down with cooling rate of 15 000 °C/s (water quench) in order to get ferrite-martensite or with cooling rate of 50 °C/s to get ferrite-bainite-martensite microstructure.

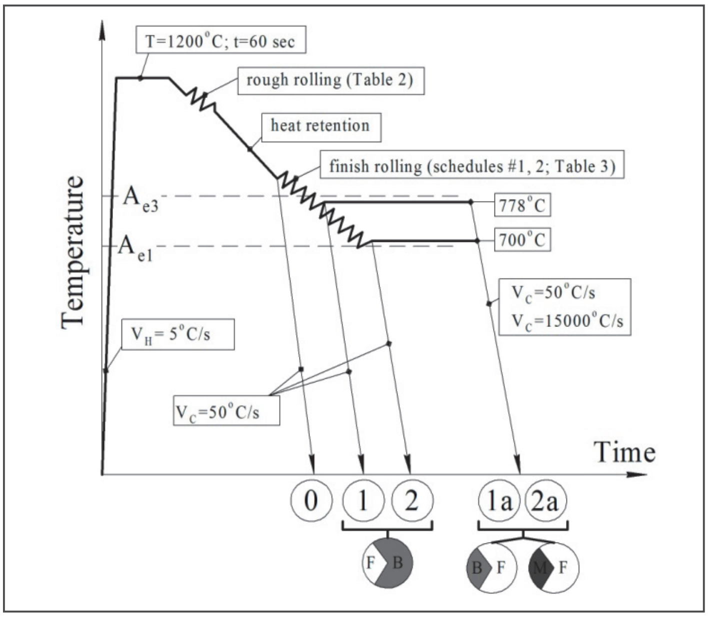

Fig. 4 The experiments scheme realized on *Gleeble-3800*

After hot rolling physical simulation microstructure (phase composition and numerical) analysis was made using images analyzer *ThixometPro* (**Fig. 5**).

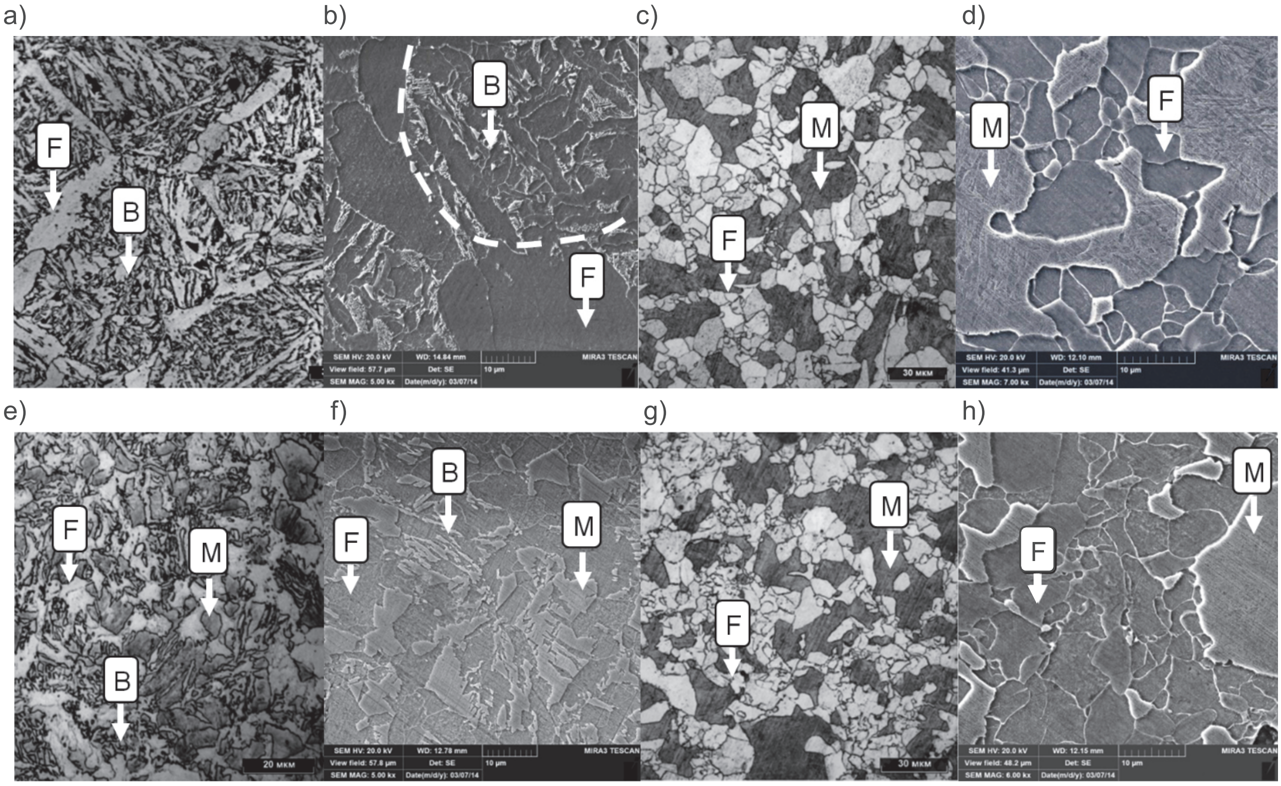

Fig. 5 The microstructures received after physical simulation according to schedules: a), b) schedule 1 (×500; ×5000); c), d) schedule 1a cooling rate 15 000 °C/s (×500; ×7000); e), f) schedule 2 (×500; ×5000); g), h) schedule 2a cooling rate 15 000 °C/s (×500; ×6000); F - ferrite; B - bainite; M - martensite

The results of specimen diameter measurement during isothermal holding at 778 °C и 700 °C according to schedules 1a and 2a are shown on **Fig. 6**. It is evident that dilatometric curve attains saturation in 500 seconds in both cases. Microstructure analysis after holding showed that during this time 65 % ferrite for the schedule 1a and 50 % ferrite for the schedule 2a are formed. This means that this is the maximum content of α-phase at those temperatures for the investigated steel.

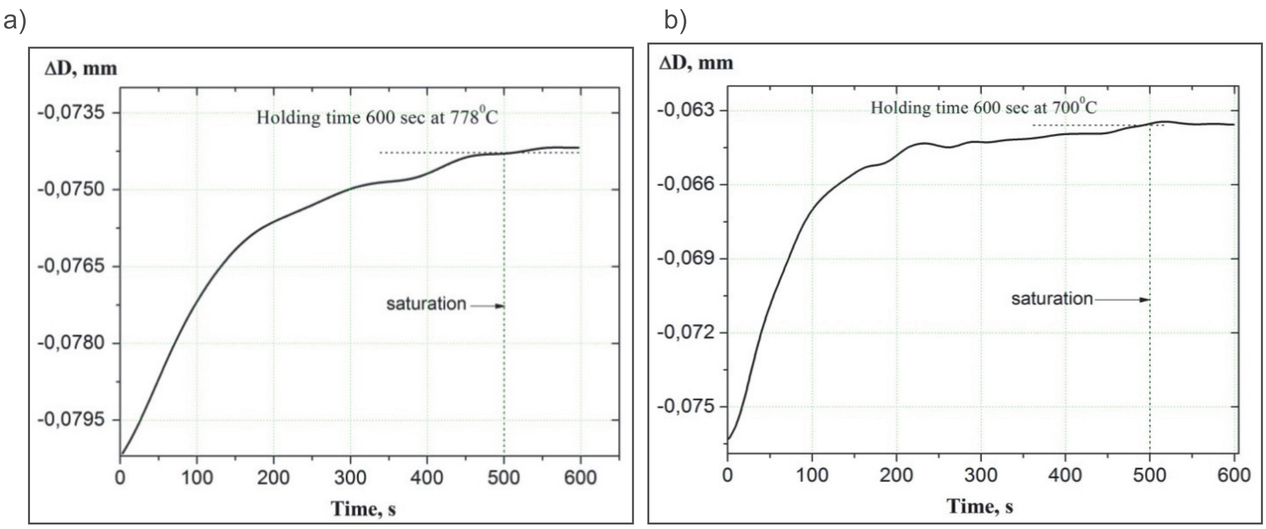

Fig. 6 Isothermal holding of 10 min for ferrite transformation: a) 778 °C; b) 700 °C

Analyzing the data obtained we can make the following conclusions:

1. The austenite average grain size after roughing rolling and holding (schedule 0) is 43.5 μm. The structure is uniform and grains recrystallized.
2. The microstructure received after schedule 1 without holding time consists of small amount of ferrite (15 %) disposed on bainite block boundaries (**Fig. 5 a, b**).
3. The microstructure received after schedule 2 without holding time consists of three phases F-B-M (**Fig. 5 e, f**).
4. The microstructure received after schedules 1a and 2a according to cooling speed consists of two phases F-M (**Fig. 5 c, d** and **5 g, h**).

The detailed microstructure analysis results (phase volume fraction, average grain size) and mechanical properties received after samples testing are presented in **Table 4**. The influence of ferrite volume fraction on received steels strength and plasticity is shown on **Fig. 7a**. Ferrite volume fraction increasing leads to strength decreasing, plasticity keeps stability and has a range from 15 to 17 %. The mechanical properties of received steels compare to steels received in different researches [4, 5] are presented on **Fig. 7b**.

Table 4 Mechanical properties and microstructure of investigated steel

Schedules	Phase	Holding	Microstructure				Mechanical properties					
			F		B	M	σ_{YS}, MPa	σ_{TS}, MPa	σ_{YS}/σ_{TS}	δ, %	ψ, %	σ_{TS}×δ, MPa·%
			%	μm	%	%						
#1	FB	-	15	15	85	-	-	-	-	-	-	-
#1a	FB	+	65	5	35	-	540	902	0,6	16	41	14883
	FM	+	65	5	-	35	795	847	0,9	7	10	5929
#2	FBM	-	40	9	30	30	812	1257	0,6	15	19	19232
#2a	FB	+	50	5,2	50	-	612	899	0,7	16	50	14384
	FM	+	50	5,2	-	50	682	995	0,7	17	24	16915

F - ferrite; B - bainite; M - martensite; δ - elongation; ψ - reduction area

a) b)

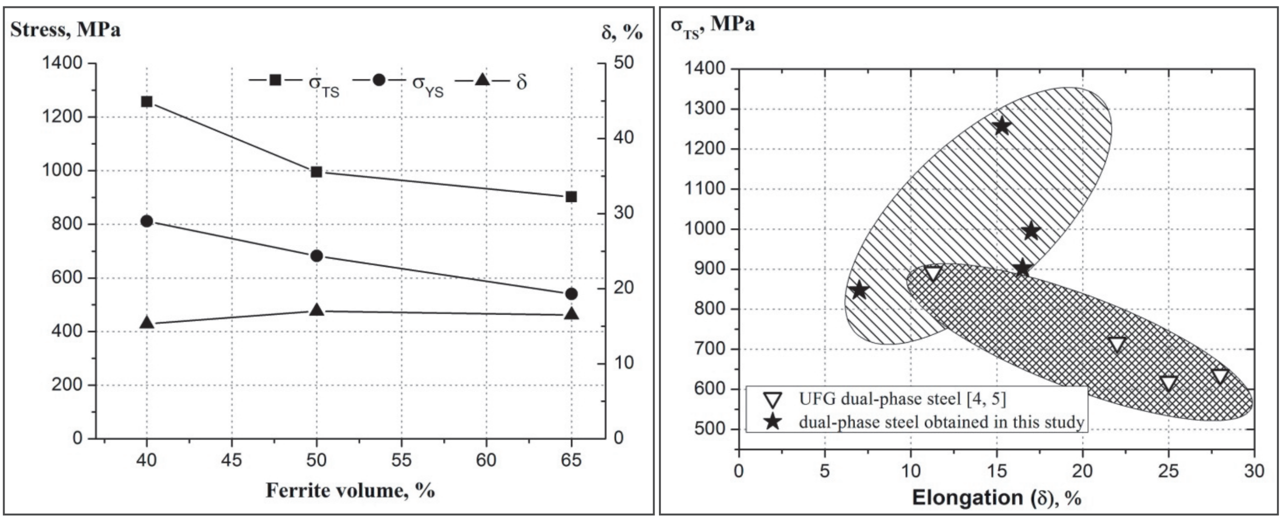

Fig. 7 The influence of ferrite volume fraction on experimental chemical composition DP-steel properties (a); mechanical properties of received steels compare to steels received in different researches [4, 5] (b)

Let us compare the results of present research with the results of the same type of steel researched by different authors (**Fig. 7** b and **Table 5**). Authors of article [4] received DP-steel after hot rolling with next properties: TS=716 MPa, YS=462 MPa, δ=22 %. Authors of article [5] received ultra fine grain structured (UFG) DP-steel after severe plastic warm deformation with subsequent intercritical annealing with next properties: TS=893 MPa, YS=452 MPa, δ=11,3 %. Therefore received in present research steel with experimental chemical composition has required level of plasticity and higher strength then analogs received by different technologies. This is mainly due that in this study, at each stage of steel hot deformation, we analytically and very finely selected processing parameters using physically based microstructure evolution mathematical models.

Table 5 Dual-phase steel chemical compositions of other authors [5, 6]

Elements	C	Si	Mn	Cr	Mo	V	Reference
Mass., %	0.2	0.42	1.56	0.21	0.2	0.03	[4]
	0.19	0.51	1.42	-	0.15	-	
	0.16	0.38	1.55	0.1	0.16	0.13	
	0.17	0.28	1.63	-	-	-	[5]

CONCLUSIONS

1. DP-steel with experimental chemical composition was received after physical simulation of hot rolling and subsequent thermo treatment on continuous mill 2000 by means of Gleeble-3800 system.
2. In order to realize developed schedules on continuous mill 2000 for producing 3 mm thickness strips with F-B or F-M microstructure the holding time 500 s after roughing rolling in temperature interval of 700-778 °C is required.
3. The best combination of strength and plasticity (σ_{YS}=812 MPa, σ_{TS}=1257 MPa, δ=15 %) was received when three phases F, B and M were received (schedule 2) after physical simulation.
4. Therefore received in present research steel with experimental chemical composition has required level of plasticity and higher strength then analogs received by different technologies.

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