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Effect of heat treatment conditions on the structure and mechanical properties of DP-type steel

J. Adamczyk, A. Grajcar*
[a] Division of Constructional and Special Materials Engineering,
Institute of Engineering Materials and Biomaterials, Silesian University of Technology,
ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: adam.grajcar@polsl.pl

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ABSTRACT

Purpose: The aim of the paper is to determine the influence of the initial structure and heat treatment conditions on mechanical properties of DP-type steel.
Design/methodology/approach: The heat treatment of the low-carbon steel in order to obtain a DP-type structure of desirable ferrite and martensite fractions was realized. In order to investigate the structure light and transmission electron microscopy methods were used. Mechanical properties were determined by means of tensile test.
Findings: It was found that a different initial structure influences essentially the martensite morphology in a final DP-type structure. It can occur as a network, fine fibres or islands in a ferritic matrix of high dislocation density in the vicinity of diffusionless transformation products of austenite. The best mechanical properties (UTS=800MPa, YS0.2=520MPa, TEl=20%, UEl=16%) has a steel with the martensite in a form of fine fibres.
Research limitations/implications: Continuation of the investigations in the field of using the thermomechanical processing to obtain a DP-type steel is foreseen.
Practical implications: The established heat treatment conditions can be useful at manufacturing DP-type sheets of high strength and ductile properties and a good suitability for metalforming operations.
Originality/value: The relationship between the initial structure and martensite morphology in DP-type steels was specified.
Keywords: Heat reatment; DP-type steel; Martensite; Mechanical properties

1. Introduction

The automotive industry aims at the production of vehicles with the low weight, fulfiling high requirements concerning the safety improvement, the reduced fuel consumption and limitation of the emission of harmful exhaust gases. In order to meet these demands, the optimization of well known materials and searching new materials with a high ratio of strength to density and the good suitability for metalforming operations are still carried out. The requirements of the automotive industry are performed in a high range by microalloyed structural steels. [1÷3]. In the modern automotive industry the hot-rolled plates of microalloyed steels are often used. Besides microalloyed steel plates, the cold-rolled sheets of BH-type (Bake Hardening) and IF-type (Interstitial Free) structure are used [4-7]. The special group of interest are steels of multiphase structure. They exhibit a superior strength-ductility balance compared to conventional steels and the required formability. These are sheets of the ferritic – martensitic structure (DP - Dual Phase) [8, 9], ferritic – bainitic structure with the retained austenite showing TRIP effect [10÷12] and complex multiphase CP-type structure (CP - Complex Phase). The interest in respect of the suitability for metalforming operations is also connected with high-manganese steels of austenitic structure. To strengthen these steels the mechanical twinning during the technological deformation is used (TWIP effect – Twinning Induced Plasticity) [13, 14].

The greatest prospects of the application in the automotive industry have DP-type steels. It is predicted [15], that their total share in a car structure can reach over 50%. These steels usually contain 0.05%÷0.2%C, 1.2÷1.6%Mn, 0.3÷0.6%Si and V, Nb and Ti microadditions of total concentration up to 0.1%. DP-type sheets can be produced by a classical heat treatment, consisting in their austenitizing at a temperature slightly higher than A_{c1} of the steel with following water quenching [16÷19] or an energy-saving technology of the thermomechanical treatment, integrating hot-rolling in the austenitic field [20÷22] or $\gamma + \alpha$ region [23÷25] with direct cooling.

The aim of the paper is to determine the influence of the initial structure and heat treatment conditions on mechanical properties of DP-type steel.

2. Experimental procedure

2.1. Material and heat treatment

The structural 0.1C-Mn-Mo steel with Ti and B microadditions was investigated (Table 1). The steel was melted using the secondary metallurgy and continuous casting of 100x100mm slabs. After solidification the slabs were hot-rolled and forged in order to obtain the rods with a section of 24x24mm. The specimens for structure and mechanical properties investigations after the heat treatment were prepared.

Table 1.
Chemical composition of the investigated steel

Mass contents in %											
C	Mn	Si	Ni	Cr	Mo	Ti	P	S	B	Al	N
0.09	1.50	0.26	0.07	0.06	0.14	0.113	0.014	0.009	0.003	0.029	0.0112

The heat treatment of the specimens was realized according to three routes, schematically illustrated in Fig. 1. In order to design suitable heat treatment conditions, the knowledge of critical temperatures A_{c3}, A_{c1} and M_s for the γ phase is needed. They were calculated using Andrews' equations:

$$A_{c3} = 910 - 203 \cdot \sqrt{C} - 15 \cdot Ni + 44.7 \cdot Si + 104 \cdot V + 31.5 \cdot Mo \quad (1)$$

$$A_{c1} = 723 - 10.7 \cdot Mn - 16.9 \cdot Ni + 29.1 \cdot Si + 16.9 \cdot Cr + 290 \cdot As \quad (2)$$

$$M_s = 539 - 423 \cdot C - 30 \cdot Mn - 17.7 \cdot Ni - 12.1 \cdot Cr - 7.5 \cdot Mo \quad (3)$$

where: C, Ni, Si, V, Mo, Cr - mass contents of the elements in the investigated steel.

The calculated temperatures of the investigated steel are: A_{c3} = 865°C, A_{c1} = 714°C, M_s = 453°C. In case of martensite start temperature, it has to be taken into consideration the carbon enrichment of the γ phase during soaking in the diphase region or the partial $\gamma \rightarrow \alpha$ transformation. It is apparent from Fig. 1 that the heat-treated steels have various initial structures. In the routes I and II, the steel was heated to a temperature of 750°C ($\gamma+\alpha$ region), hold at this temperature for 30min. and water quenched. The route III consists in austenitizing of steel at a temperature of 910°C and air cooling for 45s to a temperature of 750°C in order to realize the partial $\gamma \rightarrow \alpha$ transformation, followed by water quenching.

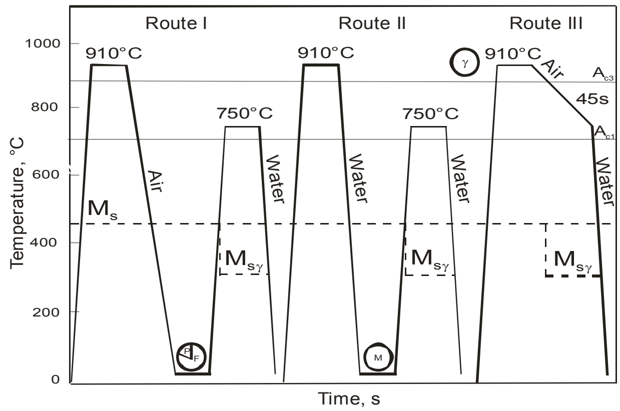

Fig. 1. Schematic representation of the heat treatment of DP-type steel according to routes I, II and III

2.2. Methodology

Investigations of the steel structure after the heat treatment were performed by means of light microscopy in the polished and etched state. The structure observations of the specimens were carried out by the use of the Leica MEF4a light microscope and observations of thin foil structure in the JEM-200CX transmission electron microscope using an accelerating voltage of 120kV. The martensite and ferrite volume fractions were evaluated by the use of the automatic image analyzer being a part of the Leica MEF 4A light microscope.

Mechanical properties of heat-treated steels were determined by means of tensile test using the Zwick Z/100 machine and the specimens with a diameter of 6mm and a gauge length of 30mm.

3. Results and discussion

An essential element of carried out investigations was to determine an effect of the initial structure of steel on the morphology of martensite in a final DP-type structure of the heat-treated specimens. Based on preliminary experiments, it was found that the initial structures for the routes I, II and III are respectively: ferrite with a small fraction of pearlite, low-carbon martensite and primary austenite with a grain size of about 12μm. A kind of the initial structure and realized heat treatment strongly influences a morphology of structural constituents of DP-type steel. The steel heat-treated according to the route I has the ferrite structure with an irregular envelope of martensite on grain boundaries (Fig. 2). It is a result of non-uniform distribution of pearlite grains on grain boundaries of the α phase and the privileged diffusion of carbon along grain boundaries during soaking of steel at a temperature of 750°C leading to the carbon enrichment of boundary-zones of the α phase and their transformation to the γ phase.

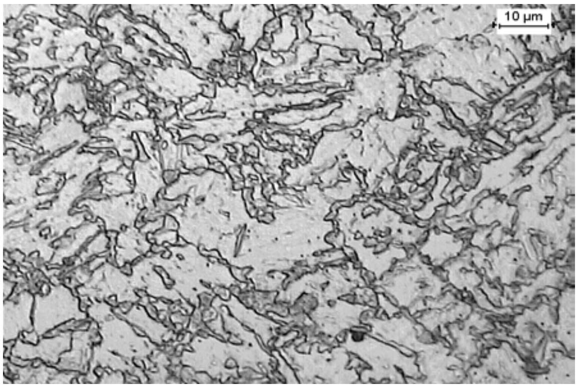

Fig. 2. Ferritic – martensitic structure of the steel quenched from a temperature of 750°C

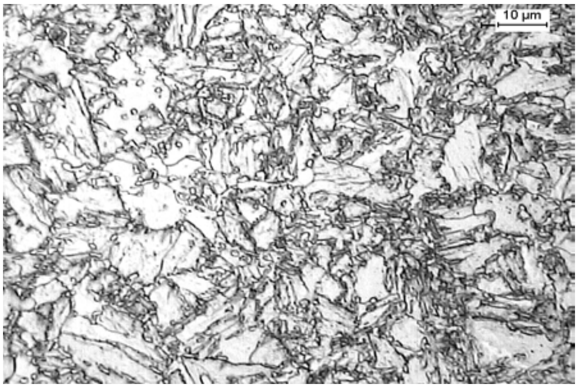

Fig. 3. Ferritic – martensitic structure of the steel twice quenched from the temperatures of 910°C and 750°C

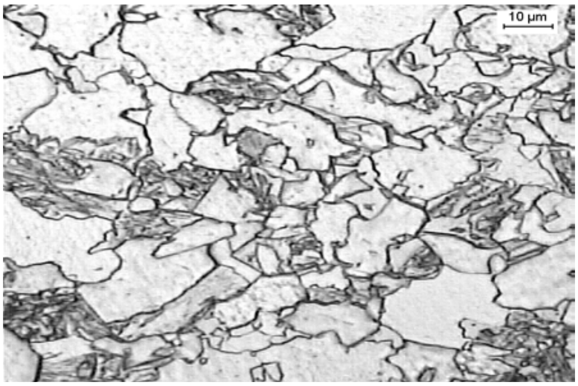

Fig. 4. Ferritic – martensitic structure of the steel quenched from a temperature of 750°C following air cooling for 45s from 910°C

The martensite fraction in the steel quenched from a temperature of 750°C equals about 22%. For this volume fraction of martensite, the carbon concentration in the γ phase equals 0.47% and the M_s temperature of this phase about 290°C. The austenite enriched in carbon increases the hardenability of steel, too. The different morphology of the structure has the steel quenched twice, i.e. from a temperature of 910°C and 750°C. In this case, during heating the steel to an underhardening temperature, the nucleation of austenite mainly occurs on the boundaries of martensite laths formed after primary quenching from a temperature of 910°C. The predominated martensite fraction occurs mainly as thin fibres located in a surroundings of grain boundaries (Fig. 3). Moreover, in a surroundings of martensite, especially at a boundary zone of large grains of the α phase, small grains of the recrystallized ferrite can be identified. The martensite fraction after underhardening for both variants of the heat treatment is near the same.

A different type of the structure specimens was found after a realization of the heat treatment according to the route III (Fig. 4). Martensite is located on grain boundaries of the α phase. The optimum fraction of martensite averaging 20% occurs after air cooling of the specimens for 45s. In order to investigate in detail the structure of DP-type steels the investigations of the thin foil structure were carried out. Figure 5 is a transmission electron micrograph showing the structure of steel water quenched following austenitizing at a temperature of 750°C. Martensite has a lath morphology and occurs as regular islands, surrounded by ferrite of high dislocation density.

Fig. 5. Martensitic island in the ferrite matrix of high dislocation density

On the basis of the tensile test, it was found that the morphology of heat-treated DP-type specimens has a fundamental effect on mechanical properties of steel (Table 2). The best connection of strength and ductile properties has the steel heat-treated according to the route II. For this variant of the heat treatment, the yield point is 516MPa, tensile strength 800MPa, total elongation about 20% and uniform elongation 16%. The steel quenched from a temperature of 750°C with an initial ferritic – pearlitic structure has lower values of the yield point and tensile strength by about 50MPa as well as total and uniform elongations by about 4%, i.e. TEl = 15% and UEl = 12%. The highest strength properties has the steel air cooled for 45s from a temperature higher than A_{c3} to a temperature of 750°C. It leads to a transformation of about 79% austenite into ferrite and a residual fraction of the austenite enriched in carbon into martensite. The yield point of the specimens cooled according to this route achieves 635MPa and tensile strength about 1000MPa.

Table 2.
Mechanical properties of the investigated DP-type steel

	Value	UTS, MPa	YS, MPa	UEl, %	TEl, %	YS/UTS	UTS · UEl, MPa · %
Route I	Mean	751	501	12.3	15.0	0.66	9282
	±	12	64	3.5	3.0	0.08	1202
Route II	Mean	798	516	16.0	19.3	0.65	12781
	±	14	54	1.1	1.2	0.06	1009
Route III	Mean	998	635	11.7	14.6	0.63	11625
	±	35	25	1.1	1.1	0.02	1180

4. Conclusions

The investigated steel is suitable to manufacture the products of the ferritic – martensitic structure by underhardening. The diversified initial structure results in obtaining DP-type steels of the various martensite morphology. A result of the quenching of the investigated steel from a temperature of 750°C is the martensite in a form of the network surrounding ferrite grains. The quenching from the temperatures 910°C and 750°C or after the partial $\gamma \rightarrow \alpha$ transformation causes that the martensite has a morphology of fine fibres or islands located in a matrix of the α phase. The used conditions of the heat treatment led in obtaining the DP-type steels of comparable fractions of ferrite and martensite. The optimum fraction of the martensite is from 21% to 24%, and a grain size of the α phase equals from 7μm to 10μm.

The diversified morphology of martensite has the influence on various mechanical properties of the steel and its deformability. The optimum strength and ductile properties has the steel quenched from a temperature of 750°C with an initial martensite structure. The yield point of this steel is about 520MPa, tensile strength about 800MPa, total elongation 20%, and uniform elongation about 16%.

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