# DESIGNING OF HOT ROLLING AND COOLING CONDITIONS FOR DUAL PHASE AND COMPLEX PHASE STEEL STRIPS

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**Abstract**

The paper focuses on rolling conditions, microstructure and mechanical properties of two different steel grades chose from the modern steel group called Advanced High Strength Steels (AHSS). The analysis carried out includes many tests and experiments such as: dilatometric and plastometric tests, Gleeble simulations of hot rolling, strip cooling after rolling and hot rolling of steel samples in laboratory conditions. For whole experimental investigations two steel grades have been chosen, namely Dual Phase (DP) and Complex Phase (CP) steels. The own casts of DP and CP steels were made, from which the samples for laboratory tests were prepared. In order to determine the cooling curves and the start and finish temperatures of phase transformations, the dilatometric investigations were performed. The designed CCT diagrams were the fundamentals of the planning of further research, e.g. computer simulation and hot rolling in laboratory conditions. On the basis of FEM analysis and plastometric tests (Gleeble), the thermo-mechanical conditions resulting in a fine-grained structure were designed. The level of diversified microstructure and thus wide range of mechanical properties by the use of laboratory hot rolling and multi-stage cooling processes were determined. It was pointed out that apart from chemical composition the thermo-mechanical rolling conditions have great influence on phase composition and mechanical properties of the investigated DP and CP steel strips. The results of the analysis carried out in this work provide useful data for the designing of thermo-mechanical rolling of DP and CP steel strips, which have multiphase microstructure and diversified mechanical properties.

**Keywords:** DP and CP steel, thermo-mechanical rolling, CCT curves, mechanical properties, hot workability

## 1. INTRODUCTION

Dual Phase (DP) and Complex Phase (CP) steel with multiphase microstructure belong to the modern steel group called Advanced High Strength Steels (AHSS) and due to their properties are used very often in the automotive industry. Third generation of these steels is now widely investigated. Practically, these steels are characterized by a compromise between high cold-workability of steel sheet and rigidity of a car body draw-piece. Dual Phase steels (DP) are a group of low-carbon micro-alloyed steels, whose structure consists of soft ferritic matrix, in which 20-70 % of martensite is distributed, **Fig. 1a**. Depending on the process route and steel composition, hot rolled strips can have a microstructure containing some quantities of bainite. The microstructure of CP steels contains small amounts of martensite, retained austenite and pearlite within the ferrite/bainite matrix, **Fig. 1b**.

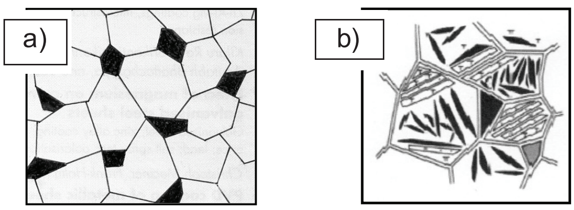


**Fig. 1** a) Islands of martensite (black) in a matrix of ferrite in DP steel, b) microstructure of CP steel

The grain refinement is created by retarded recrystallization or precipitation of microalloying elements like Ti or Nb [1]. In general, CP steels show higher yield strengths than DP steels, while tensile strengths remain on similar level for both steels. DP and CP steels are produced similarly as all AHSS steel by control cooling from austenite (or austenite and ferrite) phase. Practically, it is realized in the cooling line of hot strip mill (hot rolled products) or in the cooling section of the continuous annealing furnace (cold rolled products) [2,3,4]. However, the technology that seems to be prevailing in the future is hot strip rolling realized in modern rolling mills integrated with continuous casting of thin ingots.

## 2. CCT DIAGRAM OF COMPLEX PHASE STEEL

The new developed low carbon DP and CP type steels were investigated. Chemical composition of elaborated steels (**Table 1**) were optimized in the aim of obtanining an optimal fraction of multiphase microstructure under conditions of hot rolling and multistage cooling. Liquid metal was cast in the ingot moulds with the capacity of about 100 kg. Successively, the ingots were hot forged into flat bars of 160 mm in with and 60 in thickness, from which the specimens for dilatometric, plastometric tests and experimental rolling were machined.

**Table 1** Chemical composition of investigated DP and CP steel

| Steel grade | C | Mn | Si | P | S | Cr | Ni | Mo | Ti | Nb | Al. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DP | 0.10 | 1.49 | 0.52 | 0.01 | 0.009 | 0.04 | 0.02 | 0.01 | - | - | 0.06 |
| CP | 0.10 | 1.02 | 0.67 | 0.01 | 0.007 | 0.68 | 0.01 | 0.01 | 0.06 | 0.06 | - |

To design thermo-mechanical rolling of DP and CP steels a knowledge of their hot workability and multi-stage cooling rate is of primary importance. In order to obtain the cooling curves, the start and finish temperatures of phase transformations (critical temperatures), a cooling process was performed using dilatometer (DT1000 type). Tubular samples of 2 mm in diameter and 12 mm in length with 1 mm diameter hole were used for determination of CCT diagrams. Specimens were heated at the rate of 3 °C/s to austenitizing temperature of 1000 °C and were held for 20 minutes. Subsequently, the samples were cooled at the rate of 10 °C/s to the temperature of 890 °C, being the start of controlled cooling.

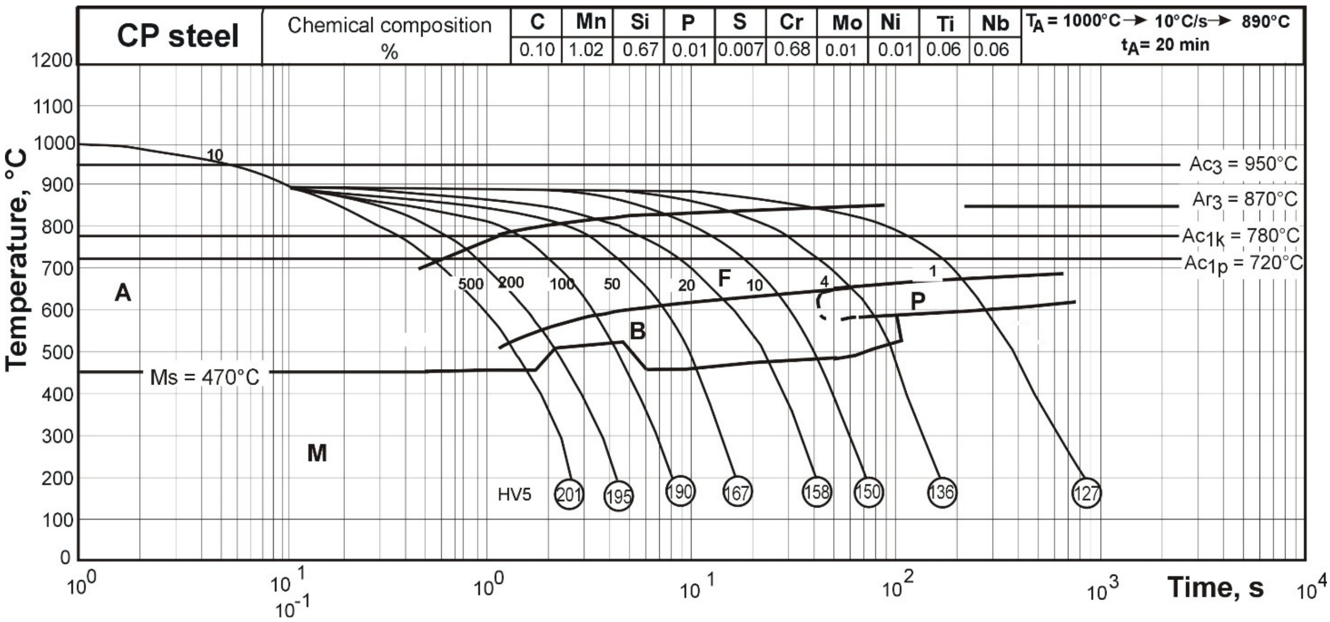


**Fig. 2** Detailed CCT diagram obtained for CP steel

Critical temperatures ($A_{c1}$ and $A_{c3}$) of the investigated steels and diagrams of cooling of deformed austenite transformations were assigned. The precise CCT diagrams are the basis for obtaining the most favourable material properties, considering further processing. CCT diagram contains the data about the start and finish temperatures of phase transformations and hardness values obtained in the cooling process with different rates. The obtained CCT diagram for DP steel is presented in [3,5] and for CP steel is shown in **Fig. 2**.

**Fig. 3** Microstructure of CP steel after controlled cooling with rate 500 °C/s (left) and 20 °C/s (right)

## 3. FLOW STRESSES

Series of tests were performed using torsional plastometer. The obtained results in a form of flow stress variations as a function of temperature, strain and strain rate were loaded into computer program as the material database. The obtained flow stresses for DP steel are presented in [2,5] and example flow stresses for CP steel is shown in **Fig. 4**.

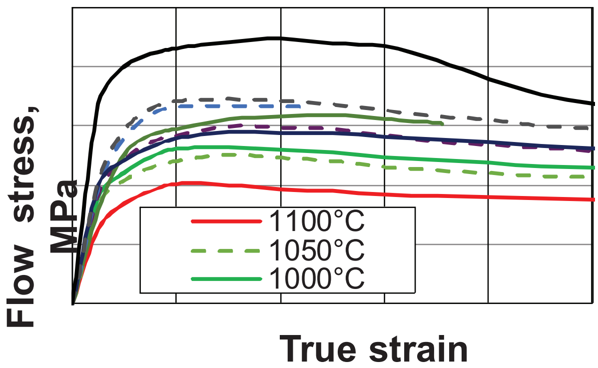


**Fig. 4** Flow stresses for CP steel obtained from torsion tests for various temperatures (in °C) and strain rate equal 2 $s^{-1}$

Multistage compression of the process of hot rolling in the six final stands, as in industrial process, was realized for DP steel with application of Gleeble 3800 simulator The cubicoid specimens of 15x20x35 mm were compressed under conditions of plane strain in the six cycle compression to the true strain of 1.15 with the final strain rate of 100 1/s.The foils were used to prevent sticking and graphite foils and Ni-based grease as lubricants. The test parameters, i.e. temperature of rolled strip, strain, strain rate and idle time between passes were selected to represent the deformation conditions occurring in real process as precisely as possible. Example result, obtained for rolling simulation of DP steel, is shown in **Fig. 5**.

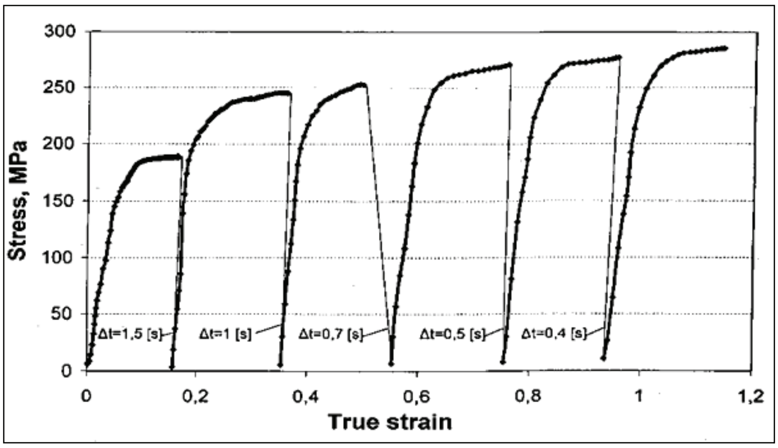


**Fig. 5** Simulation of hot rolling using Gleeble 3800 (final temperature 890 °C and strain rate of about 100 $s^{-1}$)

## 4. COMPUTER SIMULATION OF HOT ROLLING AND COOLING

For stress and strain analysis the simulation of hot strip rolling with application of computer program (FEM) has been applied [6]. The results of calculations contribute to better understanding of flow pattern of a strip in the roll stands, as well as the distributions of temperature, stresses (**Fig. 6**) and strains (**Fig. 7**) in the strip being deformed.

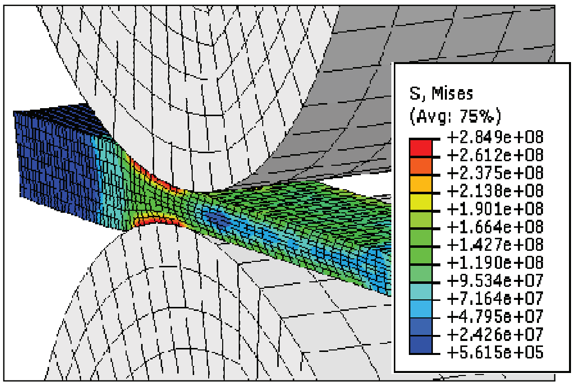


**Fig. 6** Von Misses stress during rolling in first pass

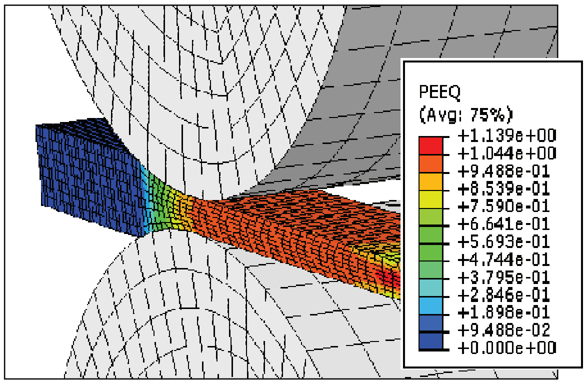


**Fig. 7** Effective strain during rolling in first pass

For simulation of strip cooling after hot rolling commercial software (*TTSteel*) was used. Cooling rates ranging from 500 °C/s to 1 °C/s were selected and simulation was performed for cooling from the temperature of 890 °C. The chemical compositions of steel as well as cooling temperature-time relationships determined by dilatometer were stored in the program database. The effect of cooling rate on phase composition and forecast mechanical properties of Complex Phase steel is presented in **Fig. 8** and **Fig. 9**. The results of calculation confirm that the cooling rate of about 20 °C/s makes it possible to obtain the ferritic-bainitic-martensitic microstructure, while at the cooling rate of about 4 °C/s only the ferritic-pearlitic-bainitic microstructure develops. The software allows for determining the critical temperatures and CCT curves for theoretical cooling with different cooling rates. It also allows for prediction phase composition and forecast mechanical properties of investigated steels. All these investigations were the basis to the planning of further research e.g. rolling and cooling parameters of DP and CP steel strips.

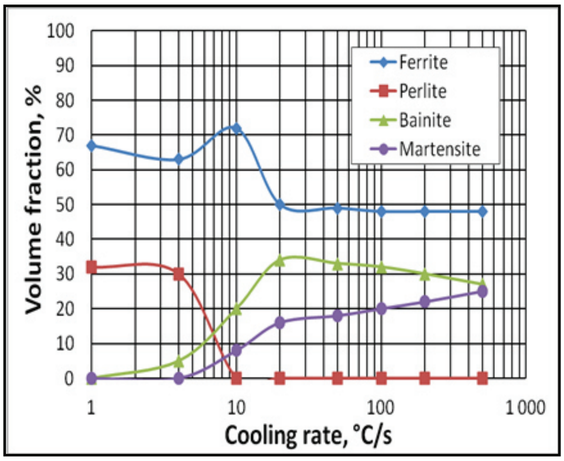


**Fig. 8** Influence of cooling rate on phase volume fractions of CP steel (results from *TTSteel*)

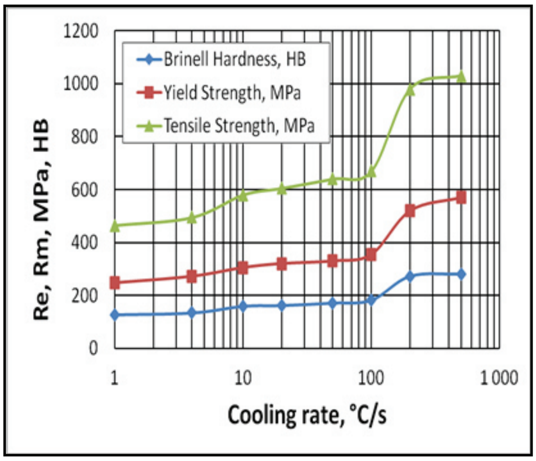


**Fig. 9** Influence of cooling rate on mechanical properties of CP steel (results from *TTSteel*)

## 5. RESULTS OF EXPERIMENTS AND DISCUSSION

The samples for experimental rolling were prepared from special cast of DP and CP steels. The flat specimens of dimensions 12.4 x 26.8 x 120 mm were used in experimental hot rolling and cooling, which schedule is presented in **Table 2**.

**Table 2** Schedule of experimental rolling and controlled cooling of DP and CP steel samples

| Series | HOT ROLLING | | | | COOLING |
|---|---|---|---|---|---|
| | Heating temperat., °C | Roll end temperature | Number of passes | Reduction in the passes, % | Cooling way/rates, °C/s |
| A-DP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | water / 100 |
| B-DP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | water spray / 15 |
| C-DP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | air / 4 |
| D-DP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | water + holding in ferrite region |
| E-CP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | 20 |
| F-CP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | 10 |
| G-CP | 1250 | below $Ar_3$ | 3 | 2 x 60 +1 x 35 | 4 |

The realized rolling of DP samples in laboratory conditions together with controlled cooling allowed for obtaining diversified steel microstructures, depending on the roll-end temperatures and the cooling rates. Some mechanical properties of strip samples obtained after experimental rolling in three passes and controlled cooling with different rates are presented in **Fig. 10** and **Fig. 11**.

The increase of cooling rate after hot rolling above the critical cooling rate results in increased martensite volume fraction in DP steel, and thus higher strength and lower formability of investigated strip samples. Martensitic phase prevails (from 66 to 70 %) when using water cooling (rate about 100 ºC/s) and thus very high strength ($R_e$, $R_m$, and HV) and low formability ($A_{50}$) of steel strips were obtained. In case of water spray cooling (rate about 15 ºC/s), the bainitic phase (41 % for B-DP samples) was formed. Thus, lower but enough high strength and better formability of strip samples were obtained. When air was used as a coolant (rate about 4 ºC/s), only ferritic-pearlitic microstructures were observed. The best results for DP steel were obtained when water cooling with holding inside ferrite region (about 7 s) was applied (D-DP samples). In this case hot rolled strips had microstructure containing much lower of martensite (19.1 %) and some quantities of bainite (11.5 %). The obtained microstructure results in adequately low yield stress ($R_e$ = 479 MPa) and high ultimate strength ($R_m$ = 786 MPa), allowing for obtaining sufficiently good $R_e/R_m$ ratio (equal 0.61) and acceptable level of cold formability ($A_{50}$ = 15 %).

Similarly, the samples of CP steel were hot rolled in three passes and then cooled with three different rates, namely 20, 10 and 4 °C/s. The increase of cooling rates results in increased martensite and decreased pearlitic volume fraction in CP steel, and thus higher strength and a bit lower formability of investigated strip samples. When low rate was used of about 4 °C/s (G-CP samples), only ferritic-pearlitic-bainitic microstructures were observed. The most desirable microstructures of CP steel are that ones which contain ferrite, martensite and bainite. Taking into account mechanical properties, the best results for CP steel were obtained when high cooling rates (about 20 °C/s) were applied (E-CP samples). In this case CP strips had microstructure containing of about 18 % of martensite, 33 % of bainite and the rest of ferrite. The obtained microstructure results in low yield stress ($R_e$ = 321 MPa) and high tensile strength ($R_m$ = 618 MPa), allowing for obtaining very good $R_e/R_m$ ratio (equal to 0.52) and good level of cold formability ($A_{50}$ = 22 %).

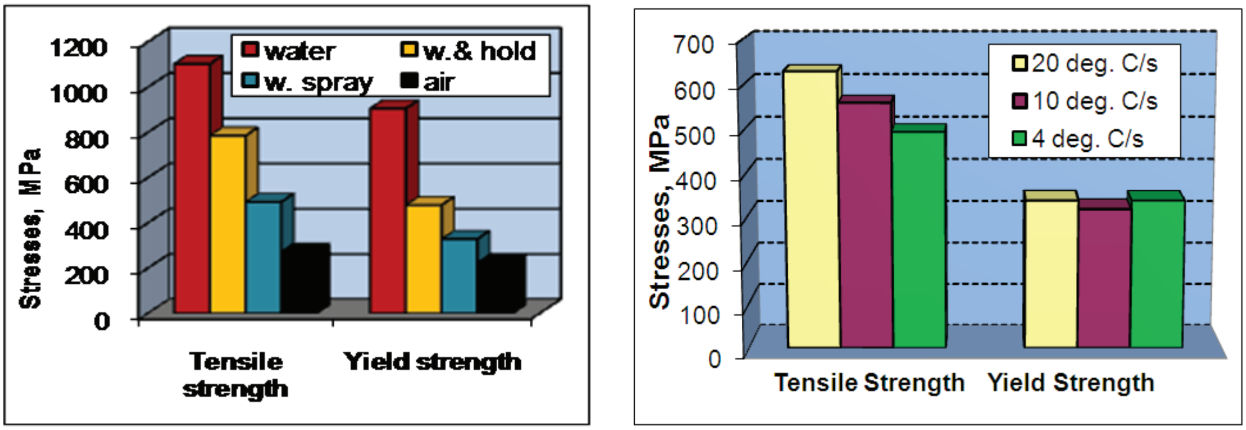


**Fig. 10** Tensile strength and yield strength for DP (left) and CP (right) strip samples rolled in three passes

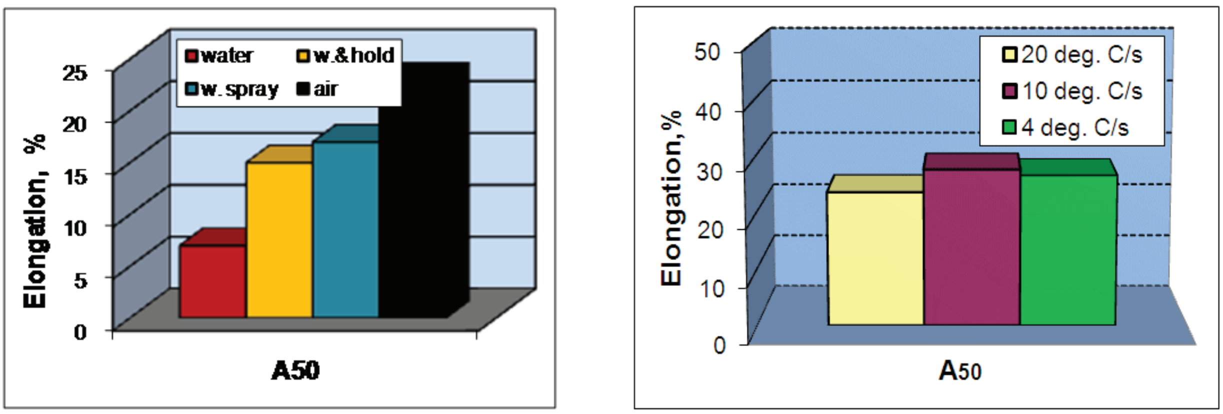


**Fig. 11** Comparison of elongations ($A_{50}$) for DP (left) and CP (right) strip samples rolled in three passes

It is reccomended for CP steel strips rolling to apply very fast cooling after deformation in the last rolling stand down to the temperature $M_s$ (martesite start) plus about 30 °C. Successively, in this temperature strips can be coiled and isothermal holded for one hour, and after that can be slow cooled to the ambient tremperature.

## 6. CONCLUSIONS

1) The most satisfactory results of experimental rolling of DP steel were obtained when water-cooling with holding inside ferrite region was applied (D-DP samples). In this case hot rolled strips had microstructure containing sufficient level of martensite (19.1 %) and some quantities of bainite (11.5 %). The obtained microstructure results in adequately low yield stress ($R_e$ = 479 MPa) and high strength ($R_m$ = 786 MPa), allowing for obtaining very good $R_e/R_m$ ratio (equal 0.61) and acceptable level of cold formability ($A_{50}$ = 15 %).
2) The obtained microstructure of CP strips results in low yield stress ($R_e$ = 304 - 321 MPa) and high tensile strength ($R_m$ = 492 - 618 MPa), allowing for obtaining very good $R_e/R_m$ ratio (around 0.55) and level of cold formability ($A_{50} \geq 22$ %). The change of the cooling rates results in greater changes in tensile strength than in yield strength or elongation ($A_{50}$).
3) The different microstructures can be obtained by choosing hot rolling and cooling parameters, thus a wide range of mechanical properties of DP or CP steel strips can be acquired. This allows rolling mills to adjust process parameters to obtain the required properties.
4) The results of the analysis provide useful data for the designing of thermo-mechanical rolling of DP and CP steel strips or adjusting existing processes to meet very high requirements demanded by the modern industry.

## ACKNOWLEDGEMENTS

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