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CHARACTERISTIC OF DP600 STEEL PRODUCED IN HOT ROLLING PROCESS

DP600 steels are characterized by a dual phase ferritic-martensitic microstructure, to which they owe their exceptionally favourable combination of high strength and good ductility. One of the production methods for this grade of steel is the hot rolling process. Despite the fact that these steels have been produced on an industrial scale for almost 40 years, they are still being studied intensively, with new research on the formation of their microstructure and properties published every year. This article focuses on the characteristics of DP600 steel produced on a hot rolling mill for applications in automotive industry. The article presents the results of mechanical properties tests and microstructure analysis of DP600 steel obtained in an industrial hot rolling process. The general characteristic of DP600 steel presented in this article, is supplemented with statistical analysis of correlations between chemical composition, selected process parameters and mechanical properties of hot rolled DP600 steel.

Keywords: Dual phase steels; hot rolling process; mechanical properties; automotive industry

1. Introduction

DP600 steel belongs to 1st generation of Advanced High Strength Steel (AHSS). It is characterized by a high tensile strength exceeding 570 MPa, continuous yielding behaviour, low yield strength (YS) to ultimate tensile stress (UTS) ratio and high strain hardening ratio [1]. Additionally, it has a high capacity to absorb impact energy, which is extremely important for the safety of car passengers [2]. All these features make DP steels frequently used in the automotive industry for body components, such as floor panels and floor reinforcements. Hot rolled DP600 with thickness of 3-6 mm is most commonly used for the production of automotive wheel discs. The favourable combination of high tensile strength and good ductility enables automotive manufacturers to reduce the weight of manufactured components while maintaining the desired strength [3]. DP steels owe their mechanical properties to their dual phase structure. In these steels, ferrite acts as a soft matrix ensuring good ductility, while martensite is present in the form of islands surrounded by ferrite. Martensite, characterized by much higher hardness and tensile strength than ferrite, is a strengthening factor in DP steels, and its presence increases both YS and UTS. The martensite volume fraction in DP600 steels is typically 10% to 15%. Obtaining a dual phase microstructure in the material after hot rolling is possible by using a special method of strip cooling after the finishing rolling (Fig. 1).

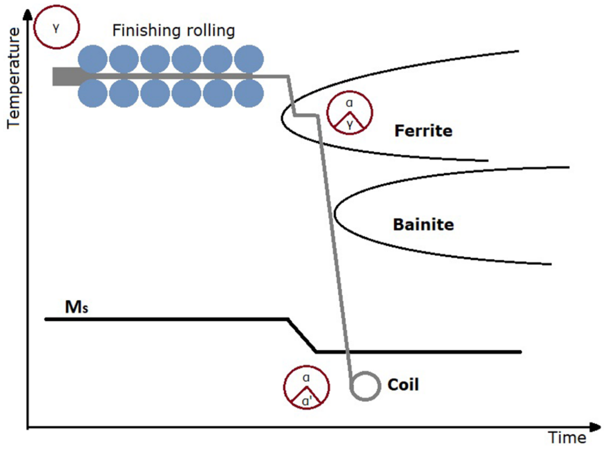

Fig. 1. Schematic diagram of strip cooling after finishing rolling

Immediately after the finishing rolling process, the strip is cooled with water at the maximum possible rate to a temperature between A_{r1} and A_{r3}. Water cooling is then stopped for a period of several seconds. During this short pause in water cooling, the transformation of overcooled austenite into ferrite takes place in

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the material. Due to the short duration of the pause in water cooling and the relatively high strip temperature of approximately 650°C, only part of the austenite is transformed into ferrite during this time [4]. The austenite remaining in the material undergoes martensitic transformation during the second stage of water cooling, which ends below the temperature of *Ms*. As shown in Fig. 1, *Ms* temperature decreases during cooling process. *Ms* decrease is caused by austenite enrichment with carbon, resulting from carbon diffusion from freshly formed ferrite into remaining austenite. Therefore, it is extremely important to maintain sufficiently low coiling temperature along whole length of the coil, so that the volume fraction of martensite would be consistent in all parts of the coil. The purpose of this article is to discuss mechanical properties and microstructure of hot rolled DP600 in context of the most recent research concerning its production and properties. Additionally, based on industrial data for over 250 hot rolled coils of DP600, correlations between chemical composition, selected process parameters and mechanical properties are presented.

2. Shaping the dual phase microstructure

Microstructure studies of commercial DP grades indicate, that the hard phase often consists of a mixture of martensite and bainite, and in some cases also retained austenite [6]. In the study, it is found that islands of martensite can have a bainitic core, what can be explained by limited diffusion of carbon within the austenite. During the pause in water cooling, austenite adjacent to the phase boundary with ferrite is enriched in carbon by diffusion from ferrite, while the interior of austenite grains, due to the slow diffusion of carbon in austenite, is poorer in carbon. This results in different hardenability of austenite grains across their volume [7]. Poorer in carbon austenite interiors undergo bainitic transformation, while richer grain margins undergo martensitic transformation. As the grain size of the primary austenite increases, the volume fraction of both martensite and bainite in the final microstructure of the material is expected to increase, since the number of privileged sites of ferrite nucleation decreases with the increase of austenite grain size. The volume fraction of austenite transformed into the ferrite during the pause in water cooling is greater the lower the temperature to which the material is cooled, which is related to the effect of the degree of austenite overcooling on the kinetics of ferrite nucleation and growth [8]. The degree of ferritic transformation increases also with the increase in the duration of pause in water cooling and with the increase in the degree of material deformation.

It is frequently reported, that increasing the surface area of the ferrite-martensite interface improves the ductility of DP steels by enhancing the deformation strengthening mechanism [9-12]. Therefore, a microstructure consisting of many fine, elongated islands of martensite is considered the most favourable, as it results in an increased ferrite-martensite interface area. The large interface area also improves impact strength. One method to achieve a microstructure with a large interface area is to apply high strain and low temperature in the finishing rolling process, as this leads to elongation of austenite grains, from which the martensite is produced during the cooling process. Another factor related to the phase morphology affecting material properties is the size and dispersion of martensite islands within the ferrite matrix [13]. Recent studies demonstrated, that martensite occurring as isolated islands has a strong positive effect on mechanical properties [13,17,20]. In comparison, bands of martensite, often formed as chains of large, interconnected islands, result in reduced ductility of the material and significantly increases the risk of cracking during the cold deformation [5].

3. Effect of microstructure on mechanical properties of DP steels

The primary factor affecting the mechanical properties of DP steels is the volume fraction of martensite [13]. With an increase in the volume fraction of martensite, an increase in strength properties is observed with a decrease in ductility. Martensite, being a hard and hardly deformable phase, is a strengthening factor in DP steels. However, it should be noted that as the volume fraction of martensite in DP steels increases, hardness of this phase decreases [15]. This effect is related to the fact that as the volume fraction of martensite increases, the carbon concentration in the martensite decreases, thus lowering its hardness. From the crack resistance point of view, it is beneficial to lower the difference in hardness between ferrite and martensite [16]. In industrial applications, this is achieved either by increasing the hardness of the ferrite, by mean of grain refinement or solid solution strengthening, or by lowering the hardness of the martensite by reducing its carbon concentration. As the volume fraction of martensite increases, the additional strengthening effect is observed resulting from unequal deformation of the two phases. This effect leads to an increase in strength without deterioration in ductility [17]. In the initial stage of DP600 deformation, only ferrite undergoes plastic deformation, while martensite deforms elastically. As the deformation of the material increases, micro voids nucleate, and are mostly formed at the ferrite-martensite interface. Their formation is related to the high inhomogeneity of the plastic properties of the two phases.

TEM and EBSD studies indicate the presence of a high dislocations density in the ferritic matrix near the ferrite-martensite phase boundary [18]. These are mobile dislocations that, together with residual stresses in the ferrite resulting from the martensitic transformation, play an important role in the initial phase of deformation. At the end of the pause in water cooling, remaining austenite, which constitutes about 15% of the material volume, undergoes martensitic transformation, which results in rapid volume increase of transformed phase. This volume expansion produces a large number of dislocations in the ferrite immediately adjacent to the newly formed martensite islands. The extremely high rate of ferrite deformation caused by the increase in the volume of the martensite is evidenced by the presence of twins in the ferrite located near the martensite islands [19].

In DP steels, four major strengthening mechanisms can be distinguished: strain strengthening, ferrite grains refinement, increase in the martensite volume fraction, and solid solution strengthening of ferrite [20]. DP steels are characterized by a high coefficient of work hardening, which is reflected in their relatively low yield strength and high tensile strength. In the hot rolling process, the ferrite grains refinement can be achieved through the use of microalloying elements (Nb, Ti, V), similarly as in the thermomechanical rolling process. The desired martensite volume fraction can be achieved by use of alloying elements that either stabilize austenite (Mn) or enhance its hardenability (Cr). Solid solution strengthening of ferrite in DP steels can be achieved similarly as in any other ferritic-pearlitic steels. One of the most significant features of DP steels from the cold formability point of view is its continuous yielding behaviour. This advantage of DP steels is related to the already mentioned dislocations accumulated in ferrite adjacent to the islands of martensite [1,3,18,21]. These dislocations, together with accumulated stress in the ferrite near the phase boundaries, facilitate the initiation of plastic deformation of the ferrite, so that the material does not exhibit a distinct yield point. DP steel after the tempering process exhibits a distinct yield point, and this can be attributed to the recovery process and associated reduction in dislocation density or it can be due to the formation of Cottrell atmospheres of carbon atoms around the dislocations.

4. Material and experiment

Studies of the microstructure and mechanical properties were carried out on samples of DP600 steel grade taken from steel sheets produced in the hot rolling process. Correlations study was carried out on the base of 259 hot rolled coils. Chemical composition of each heat was measured before continuous casting process. One heat consists of about 300 tons o metal, which corresponds to 12 hot rolled coils. During hot rolling process, a number of process parameters is measured and recorded, and this readings were also used in correlations study. Mechanical properties of hot rolled DP600 steel were measured in the tensile tests on samples taken from head-ends and tail-ends of each coil in transversal and longitudinal direction. TABLE 1 shows basic statistic calculations of chemical composition and mechanical properties of a population of 259 hot rolled coils investigated in this study.

TABLE 1

Chemical composition and mechanical properties of investigated hot rolled DP600

Variable	Mean	StDev	Min.	Median	Max.
C [wt. %]	0,072	0,0033	0,067	0,073	0,082
Si [wt. %]	0,138	0,0109	0,116	0,140	0,174
Mn [wt. %]	1,078	0,0124	1,055	1,080	1,124
YS [MPa]	371	17,6	322	371	425
UTS [MPa]	593	12,1	550	594	635
Elongation [%]	30,1	1,5	24,8	29,9	34,1

Steel slabs with a thickness of 220 mm and weight about 25 tons each were reheated in a walking beam furnace for 160 minutes to a temperature of 1250°C. After discharging from the furnace and removing the primary scale, the slabs were rolled in 7 passes in a reversing roughing mill. The thickness of the strip after the roughing rolling process was 35 mm, and the measured temperature of the strip after the last pass in the roughing rolling mill was in the range of 1030-1060°C. The next stage of the process was finishing rolling in a group of 6 rolling stands. The strip temperature measured after the last rolling stand was about 830°C. Final finishing rolling speed (FRS) varies along the strip length. At the head-end of the strip FRS is about 5 m/s and steadily increases during rolling, reaching up to 7 m/s at the strip tail-end. After leaving the last rolling stand, the strip was cooled down as described earlier using an approximately 10 s pause between the two water cooling stages. The coiling temperature of the strip was about 150°C. Coils were then stored at the coil yard for 12 hours, and then pickled in continuous pickling line.

Tensile tests were carried out on standard dog bone samples. Samples cross section was 4.2×20 mm and the initial gauge length was 50 mm. In industrial practice, samples for tensile tests or evaluating the material's microstructure are usually taken from the head-end or tail-end of coils after cutting off several meters of the strip. DP600 sheet, due to its use in the automotive industry, is pickled with hydrochloric acid after hot rolling to remove the scale from its surface before shipment to the customer. Sometimes, for technological reasons, some coils are split in the pickling line so that samples can be taken for testing from the middle part of the coil. Taking advantage of such an opportunity, for the purpose of tensile tests, impact tests and fracture analysis, samples were taken from two coils that were split on the pickling line. Samples from coil number 718 were taken 130 m from the beginning of the hot rolled coil, while samples from coil number 722 were taken 360 m from the beginning of the hot rolled coil.

5. Results and discussion

5.1. Microstructure, properties and fracture analysis

Material investigated in this part of the research was taken from a hot rolled sheet 4.2 mm thick and 1340 mm wide. The typical microstructure of DP600 steel obtained by hot rolling process is characterized by a martensite volume fraction of about 10-15%. Martensite usually occurs in the form of dispersed islands of varying size and irregular shape. Micrographs of the specimens etched with Nital etchant are shown in Figs. 2 and 3.

On micrographs, martensite can be seen as darker islands surrounded by a light ferritic matrix. Pearlite can be often found in a dual-phase steel microstructure. Its presence is usually unwanted, due to its detrimental effect on cracking resistance during cold forming. In Fig. 3, bands of the martensite can be observed.

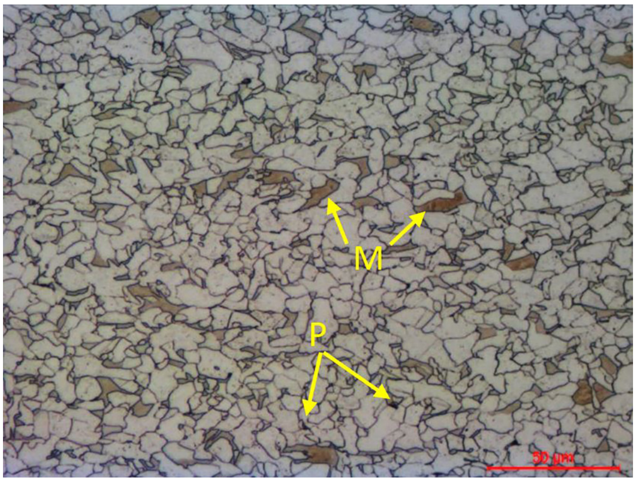

Fig. 2. DP600 microstructure close to the hot rolled strip edge. M – martensite islands, P – pearlite

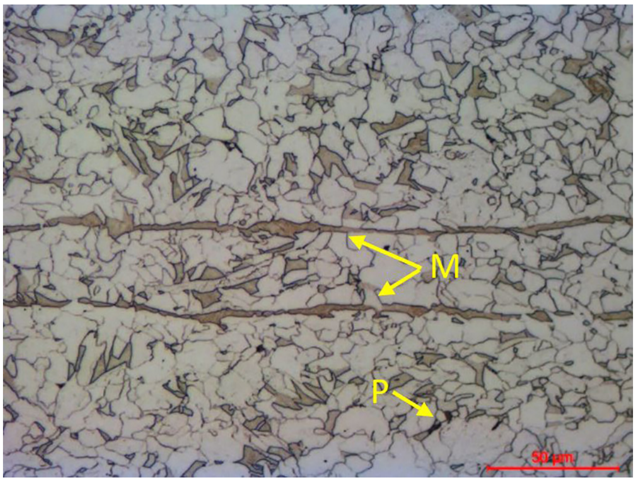

Fig. 3. DP600 microstructure in the middle part of the hot rolled strip

TABLE 2

Tensile tests results for specimens taken from the middle part of hot rolled coils

Sample	YS [MPa]	UTS [MPa]	A [%]	RD
718_1	368	615	32.3	0º
718_2	368	619	30.6	0º
722_1	374	606	33.4	0º
722_2	380	600	31.8	0º
718_3	366	604	33.4	45º
718_4	366	603	34.0	45º
722_3	360	580	33.8	45º
722_4	361	578	34.0	45º
718_5	374	626	29.0	90º
718_6	369	626	29.0	90º
722_5	375	604	30.0	90º
722_6	377	602	30.0	90º

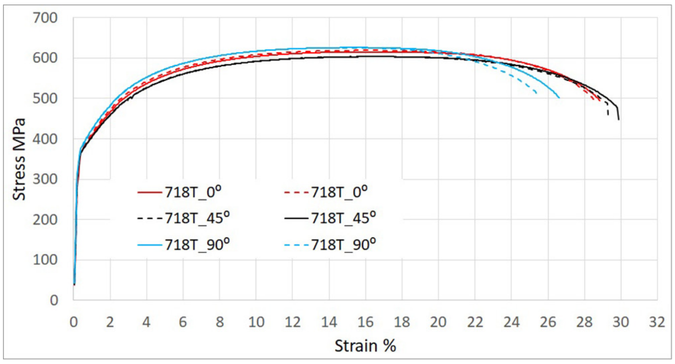

Fig. 4. Tensile curves for samples taken from coil no. 718. Solid lines – test no. 1; dashed lines – test no. 2

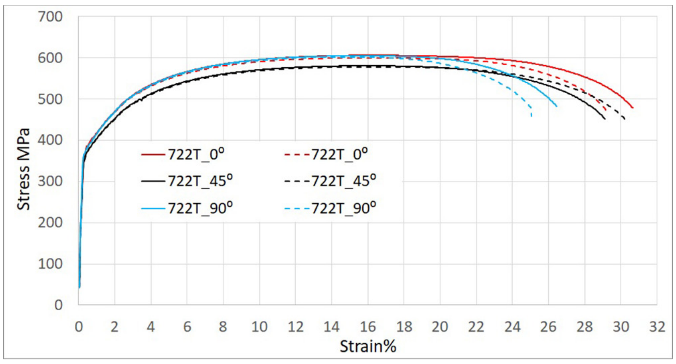

Fig. 5. Tensile curves for samples taken from coil no. 722. Solid lines – test no. 1; dashed lines – test no. 2

Mn concentration is often higher in the middle section of hot rolled strip. It can be due to Mn segregation during casting, or due to austenite enrichment in Mn during ferrite formation below A_{r3} temperature. Manganese, as an austenite stabilizer, delays the onset of ferritic transformation, hence areas rich in it are more likely to undergo martensitic transformation in the second stage of water cooling. Due to fast moving crystallization front from the side of continuously cast slab, risk of Mn segregation close to the edge of the slab is significantly lower, hence no martensite bands are visible on micrograph taken close to the edge of the strip. TABLE 2 shows the results of the mechanical properties obtained in the tensile test carried out on samples taken from the middle parts of the two hot rolled coils of DP600 steel.

Samples were taken at three angles relative to the rolling direction. The tensile curves of the samples taken from both tested coils are shown in Figs. 4 and 5.

Based on the tensile tests results, it can be concluded that DP600 steel is characterized by a certain degree of anisotropy of mechanical properties. Samples taken at an angle of 90° with respect to the rolling direction (RD) are characterized by the lowest elongation, while the differences in elongation between the samples taken at angles of 0° and 45° are very small. Samples taken at an angle of 45°, on the other hand, have the lowest UTS value. TABLE 3 shows the results of the impact tests carried out at two different temperatures. Impact tests was performed on nonnormative samples (cross section 4.2 × 4.2 mm), since the thickness of examined hot rolled strip was 4.2 mm. Measured fracture work serves a purpose of comparison of material toughness in different temperatures and at two different angles to rolling direction. A total of 20 samples taken along and across the rolling direction were tested.

TABLE 3

Impact tests results – fracture energy

T	RD	IT1 [J]	IT2 [J]	IT3 [J]	IT4 [J]	IT5 [J]	Avg. [J]
–40°C	0°	46.6	47.1	46.2	48.5	46.4	47.0
	90°	37.5	37.7	38.1	39.1	41.9	38.9
20°C	0°	51.3	48.0	55.3	51.9	50.3	51.4
	90°	49.3	47.9	49.4	49.3	49.0	49.0

Slight differences in the fracture work can be seen depending on the direction of sampling. The fracture work at the temperature –40°C was lower than at the temperature 20°C. In order to analyse the failure mechanism of the material, images of the fractures after the tensile tests were taken. The SEM images shows the fracture after the tensile test of a sample taken in transversal (Fig. 6) and longitudinal direction (Fig. 7). In both cases, the fracture has a ductile character with visible dimples, typical for materials characterized by a good cold formability. Non-metallic inclusions can also be observed, which are the sites of preferential nucleation of microcracks during the deformation. Both fractures have similar character, meaning that the fracture mechanism is the same regardless of the direction of sampling.

Fig. 8 shows an image of the specimen fracture taken under a light microscope. The darker areas in the image are islands of martensite. It can be observed that martensite undergoes relatively small plastic deformation. The degree of elongation of martensite islands in the tensile direction is insignificant. This observation is consistent with literature reports on the leading role of ferrite in the plastic deformation process of DP steel.

Results presented in this part of the work revealed some local differences in microstructure and mechanical properties. In next section, a few selected correlations are presented, aiming to identify the influence of chemical composition and some of the process parameters on mechanical properties of DP600 steel.

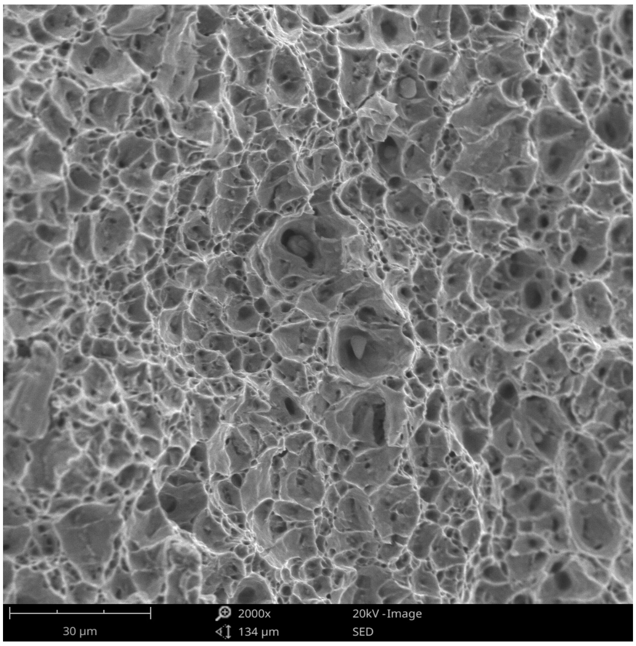

Fig. 6. SEM image of fracture after tensile test – sample transversal to RD

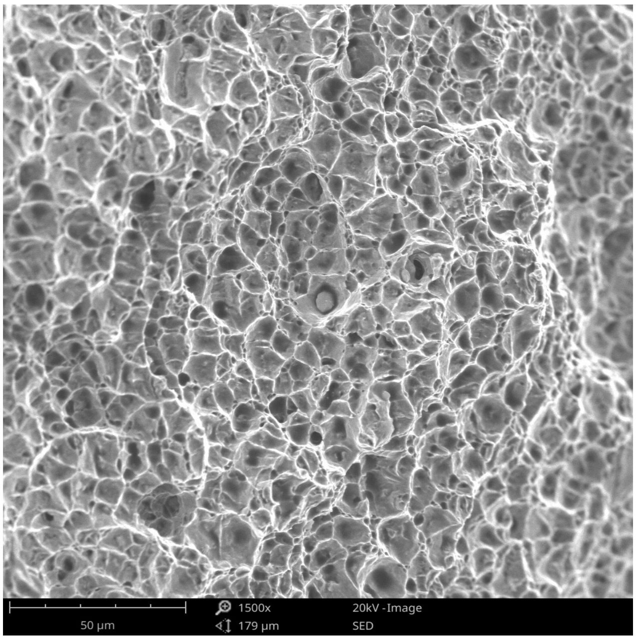

Fig. 7. SEM image of fracture after tensile test – sample longitudinal to RD

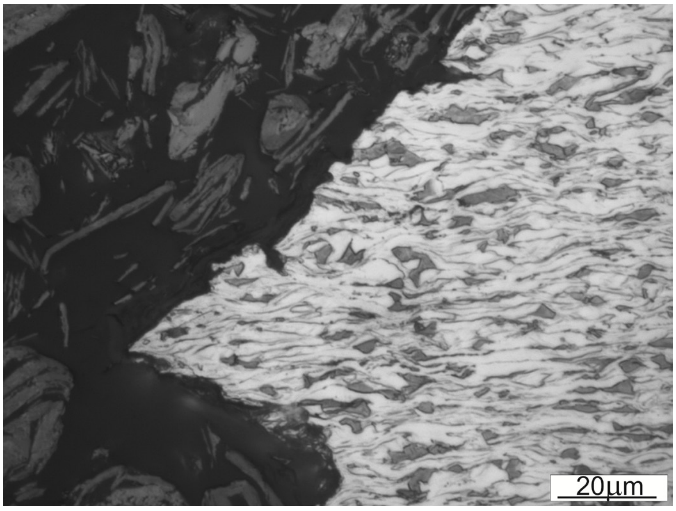

Fig. 8. Light microscope image of fracture after tensile test

5.2. Correlations study

Correlations study was carried out on 259 hot rolled coils produced in 13 separate rolling campaigns. Thickness of the strips was 4,2 mm (141 coils), 4,4 mm (11 coils) and 4,5 mm (107 coils). First observation is, that there is noticeable difference in yield stress between samples taken form head-ends and tail-ends of the coils (Fig. 9).

YS measured at the ends of hot rolled strips is on average about 16 MPa higher than on its initial parts. It may be caused by the differences in rolling speed and the strip cooling rate occurring along the strip length. Figs. 10 and 11 shows correlations between the content of C and Si and UTS (Fig. 10.) and elongation (Fig. 11). Higher content of both C and Si leads to higher UTS. It can be explained by the fact, that higher C concentra-

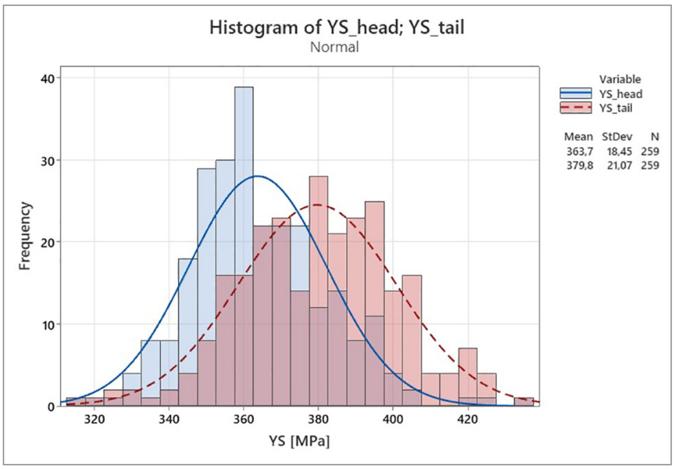

Fig. 9. Histograms of YS measured on samples taken from head-ends and tail-ends of hot rolled strips

tion in martensite increases its hardness, thus increasing overall strength of dual phase material. Additionally, both C and Si are known to improve strength of ferrite by solid solution strengthening mechanism. Those two elements have opposite effect on materials elongation, which is in good agreement with the fact, that increase of material strength by solid solution strengthening deteriorates its ductility. Same can be said about the increase in hardness difference between the two phases in dual phase steels.

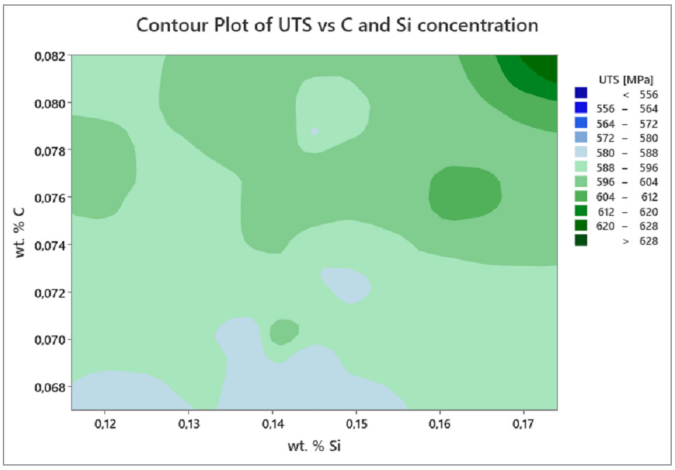

Fig. 10. Correlation between C and Si content and UTS

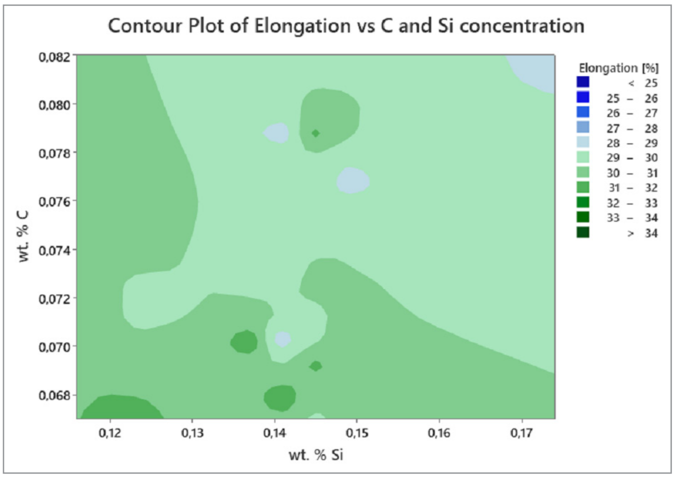

Fig. 11. Correlation between C and Si content and elongation

The correlation between UTS and elongation is confirmed by statistical analysis of tensile tests results shown in Fig. 12. A moderate negative correlation with Pearson's Correlation Coefficient *r* = –0,570 was calculated based on average UTS and elongation values measured on examined coils of DP600 steel.

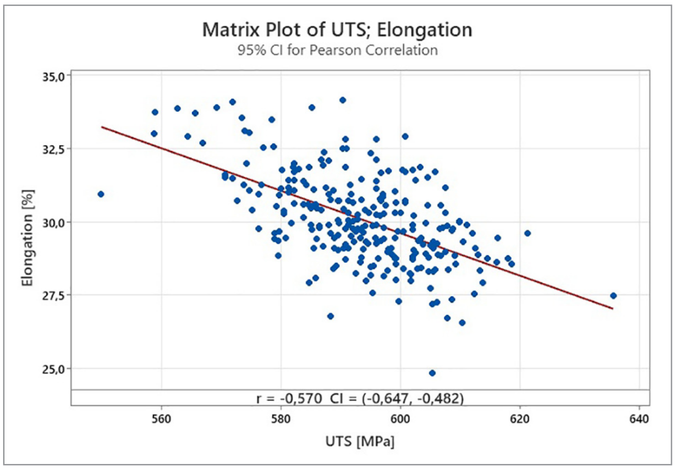

Fig. 12. Correlation between UTS and elongation

Among many hot rolling process parameters that influence mechanical properties of DP600 steel, perhaps the most critical are intermediate temperature (IT) and coiling temperature (CT). Intermediate temperature is measured during the air cooing stage of the strip cooling process (between the first and second water cooling stages). Coiling temperature is measured immediately before coiling of the strip, which is right after the end of the strip cooling process. Figs. 13 and 14 shows the effect of these two temperatures on mechanical properties of DP600 steel.

It can be seen, that high values of both IT and CT are detrimental for UTS of the steel. Both too high IT and CT can lead to formation of bainite instead of martensite, which results in much lower strength of the hard phase. If CT is too high, the cooling can

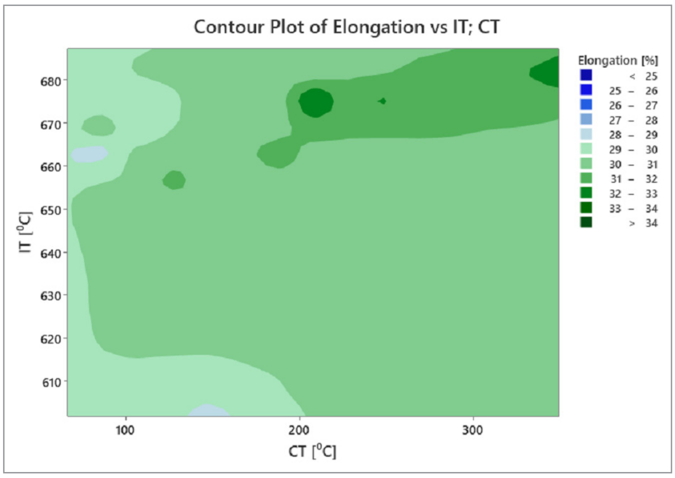

Fig. 13. Correlation between IT, CT and UTS

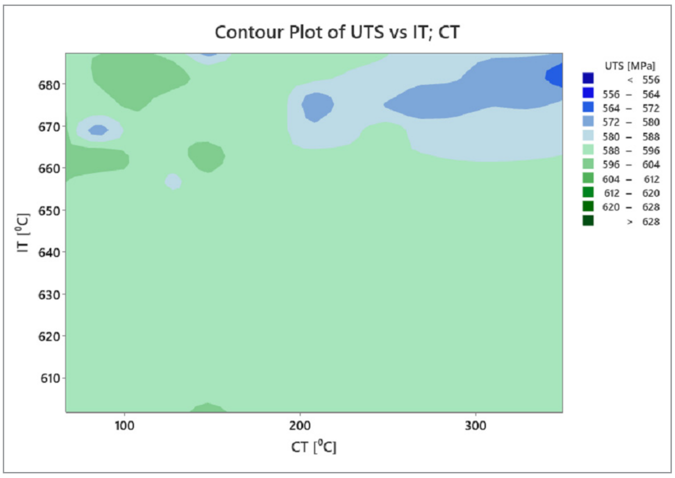

Fig. 14. Correlation between IT, CT and elongation

stop above M_S temperature. If IT is too high, the volume fraction of austenite at the end of the first stage of water cooling will be greater. This will result in lower C concentration in austenite, which lowers its hardenability. This, on the other hand, clearly improves elongation, which can be also explained by slightly better ductility of bainite compared to martensite.

6. Conclusions

Commercial DP600 steel obtained by hot rolling process is characterized by a high tensile strength of about 600 MPa, a relatively low yield strength of about 360 MPa, and high elongation, usually exceeding 30%. Hot rolled DP600 exhibits relatively isotropic mechanical properties. The biggest difference is observed on elongation, where average elongation of samples taken in transversal direction was 29,5% compared to 32% on samples taken in longitudinal direction. Fracture analysis confirmed ductile character of this steel, where soft ferritic matrix plays a leading role in plastic deformation of the material. The hard martensitic phase undergoes little plastic deformation, and this observation is in good agreement with reports from other research. Comparison of YS measured on samples taken from head-ends and tail-ends of hot rolled strips revealed a significant difference of about 16 MPa in mean values calculated for 259 hot rolled coils. This difference may be caused by change in finishing rolling speed during rolling of one strip. Statistical analysis of correlations between chemical composition, hot rolling process parameters and mechanical properties conducted on relatively large set of data from industrial hot rolling process revealed, that higher content of C and Si results in increase of UTS and decrease of elongation. It is also evident, that in case of dual phase steels, increasing UTS leads to decrease in elongation, and the correlation coefficient between the two is moderate. Another finding is, that the two key temperatures during the strip cooling process – intermediate and coiling temperature – play important role in shaping of DP600 mechanical properties. Increase in either of these two temperatures results in increase of UTS and decrease of elongation.

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