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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF DUAL-PHASE STEEL

MIKROSTRUKTURA I WŁASNOŚCI MECHANICZNE STALI DWUFAZOWEJ

The paper presents results of microstructure and mechanical properties of the dual phase (DP) steel plate with 12 mm thickness produced by intercritical annealing at a two-phase region of ferrite and austenite ($\alpha + \gamma$) and direct quenching in water. In addition the tempering treatment at temperature of 650°C was applied to investigate effect of martensite softening on mechanical properties of the tested steel. The parameters of heat treatment were designed to achieve the high strength while retaining optimum impact strength of the DP steel.

Keywords: dual-phase (DP) steel, intercritical annealing, quenching, mechanical properties

W pracy przedstawiono wyniki badań własności mechanicznych i mikrostruktury stali dwufazowej (Dual-Phase Steel) w postaci blachy stalowej o grubości 12 mm otrzymanej w wyniku międzykrytycznego wyżarzania w obszarze występowania ferrytu i austenitu ($\alpha + \gamma$) z następującym hartowaniem w wodzie. Dodatkowo przeprowadzono obróbkę cieplną uzyskanej stali dwufazowej na drodze odpuszczania w temperaturze 650°C w celu określenia wpływu zastosowanej obróbki na zmianę własności mechanicznych. Parametry obróbek cieplnych były ukierunkowane na osiągnięcie wysokiej wytrzymałości przy jednoczesnym zachowaniu optymalnej udarności badanej stali dwufazowej.

1. Introduction

High strength weldable steels are still widely used as the materials for the burdensome and responsible construction elements as well as machine parts. This type of materials is applied in the normalized state and after appropriate heat or thermo-mechanical treatment, which results in an increase of strength without modification the chemical composition by the expensive alloy additions. These properties allow to use DP steels as the construction elements exposed to the high static and dynamic loading. Welding is the most commonly used technique of joining parts made of structural steel. Recently in order to keep high weldability of structural steels the carbon content should be even below 0.1% and not as was believed earlier below 0.2% [1]. Reduction of the carbon content in the structural steel causes that the different ways leading to the increase of the mechanical properties should be used. For example: the application of the microalloying in the form of Nb, Ti, V to control the grain size and recrystallization temperature of austenite; the use of controlled thermo-forming processes, as well as obtaining low-temperature transformation products of austenite [2].

The recent method of mechanical properties design in the structural steel is the technique of incomplete quenching process from two-phase $\alpha + \gamma$ zone [3]. As a result of this treatment the two-phase DP (Dual Phase) ferritic-martensitic or ferritic-bainitic microstructure depended on the cooling rate is obtained. An important advantage of such grade of steels is the possibility of the microstructure and properties formation directly in the process of controlled rolling combined with accelerated cooling [4]. DP steels as thin sheets are widely used in the automotive industry for the purpose of deep-drawing process.

The studies to search of high-strength steels, the so-called AHSS (Advanced High Strength Steels) were undertaken in cooperation with suppliers of automotive steel. According to the research within the program ULSAB-AVC (Ultra Light Steel Auto Body – Advanced Concepts Vehicle) application in 85% of AHSS steels can reduce weight of elements about 25% without increasing production costs. The vast majority of car body components is made of DP steels. Due to its specific microstructural features, ferritic-martensitic steel type DP is an attractive combination of strength and ductility properties [5].

So far the studies related to the DP steels were carried out on materials mostly used as sheets in the automotive industry. Their thickness usually does not exceed 2 mm. This is due to the heat treatment and the requirements of the material preparation connected with the equal percentage of the individual phases on the whole cross-section. High strength properties combined with sufficient ductility qualify the DP steels for use also on higher-volume parts with large cross sections. In the following paper an attempt at modeling of the heat treatment of plates with 10-12 mm thickness while maintaining high mechanical properties combined with good fracture toughness is presented.

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TABLE 1

Chemical composition of the steel tested

element	C	Mn	Si	Mo	S	P	Cr	Ni	Cu	Al	Nb	Ti
Content wt%	0.15	1.03	0.31	0.23	0.013	0.025	0.85	0.12	0.21	0.02	0.004	0.0042

2. Experimantal

The low-alloy structural steel with the chemical composition shown in Table 1 and basic mechanical properties given in Table 2 was tested.

TABLE 2

Mechanical properties of the steel as received

YS MPa	UTS MPa	A %	HV	KCV J/cm^2
247	488	34	175	194

Where: YS-yield strength, UTS- ultimate tensile strength, A-total elongation,

HV-Vickers hardness, KCV-Charpy impact toughness

Based on the literature review [6-8] and own studies the following scheme of heat treatment of the steel was selected [Fig. 1]. First of all, the sample was normalized at the temperature of 870°C for 30 min and then two schedules of heat treatment were applied:

1. austenitizing at 900°C followed by a cooling rate of 7°C/min and then intercritical annealing for 10 minutes at temperatures: 650, 675, 700, 725, 750, 775, 800 and 825°C and direct quenching in water,
2. austenitizing at 900°C followed by a cooling rate 7°C/min and intercritical annealing for 10 minutes at temperatures: 650, 675, 700, 725, 750, 775, 800 and 825°C, direct quenching in water and tempering at 650°C.

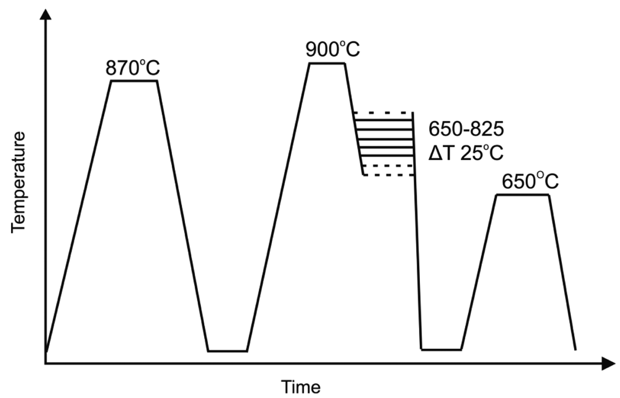

Fig. 1. Scheme of the heat treatment of the tested steel

The microstructure characterization of the subjected steel in delivery state and after heat treatments was done using the metallographic (Nikon Eclipse ME 600 with digital recording) as well as the scanning electron microscope (SEM, JOEL JSM 5510LV). The microscopy observations were performed on longitudinal section of metallographic specimens etched in 4% solution of nitric acid in ethanol (4%HNO_3). In order to obtain high contrast during the SEM observations, the samples were subjected to deep etching.

In addition to determine the volume fraction of the phases stereological measurements were carried out. Stereological parameters were analyzed using a computer-image analysis by Aphelion software company ADCIS 3.2 and Image J by Wayne Rasband at the National Institutes of Health, USA [9]. For the samples after each heat treatment type a twenty fields of view were analyzed using the following parameters:

– Zoom lens: x500,
– Single surface of the analyzed fields: 0.060 mm^2,
– Total area of analysis: ≈ 1 mm^2.

To determine the best combination of strength and ductility properties after the heat treatment detailed investigations of mechanical properties were performed. Therefore Vickers hardness measurements based on the PN-EN ISO 6507-1:2007 norm as well as impact tests according PN-EN 10045-1:1994 standard on samples with dimensions of 10×10×55 mm with notch 2 mm V-shaped were done. Static tensile tests conducted on a hydraulic testing machine EU-20 using the samples 5 mm in diameter and initial length 25 mm at room temperature were carried out according to EN 10002-1:2001 standard.

3. Results an discussion

The SEM observations of the steel in the delivery state after normalization revealed the ferrite-perlite microstructure (Figs. 2a and 2b). Whereas the samples after incomplete quenching were characterized by two-phase microstructure: ferrite-martensite (Figs. 2c-f, 3a and 3b). The ferrite phase appeared in the form of small equiaxed grains characterized by low microhardness. The second phase presented in Fig. 2, characterized by coniferous morphology and higher microhardness. It was identified as martensitic islands. The metallographic and SEM observations revealed a strong variation of the microstructure depending on of the heat treatment temperature. In the case of the samples treated at low temperature from ($\alpha + \gamma$) region, mainly ferrite phase but also a small amount of martensite located at grain boundaries were observed (Fig. 2c and 2d). The increase of temperature caused an increase of martensite volume in the steel.

The martensite obtained after quenching from 750°C was characterized by coniferous microstructure (Figs. 2e and 2f), whereas at high temperature tempering of two-phase range the micro structure changed in the form of strip (Fig. 3a and 3b), similarly by quenching at 825°C, as shown in Figure 3c and 3d.

Additionally, metallographic observations of the samples after tempering confirmed the changes in the morphology of the microstructure. After tempering inside the grains of tempered martensite very small carbides precipitations were observed in range of magnification from x3000 to x5000, whose diameters did not exceed 0.2 μm. The microstructures of the samples from low temperature of quenching were presented in Figures 4 and 5.

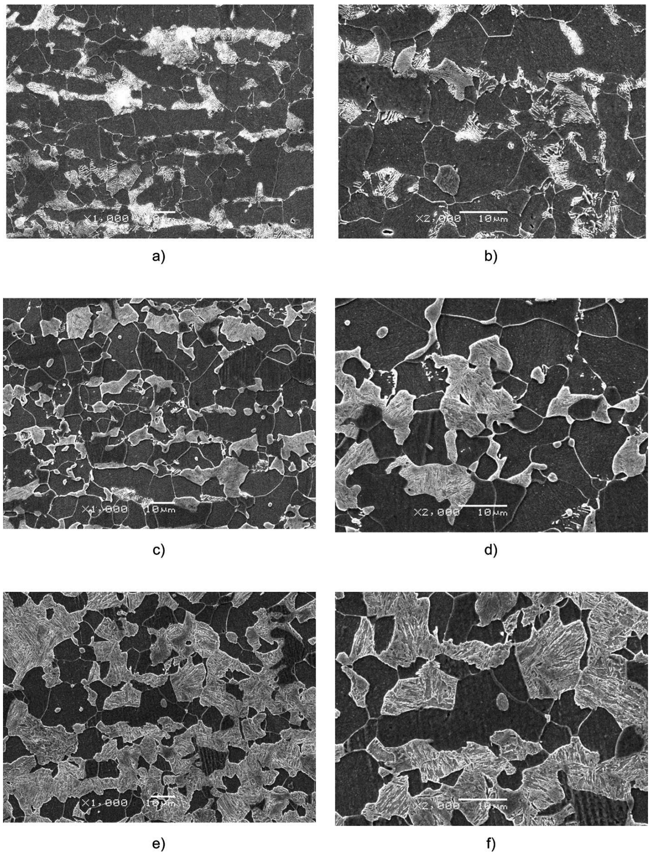

Fig. 2. SEM microstructure of the steel, etched in 4% HNO_3 : a, b) in delivery state; c, d) after quenching from 700°C e, f) after quenching from 750°C

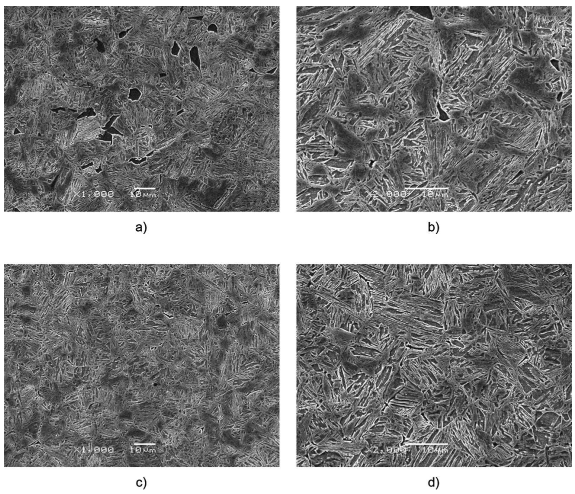

Fig. 3. SEM microstructure of steel etched in 4% HNO_3: a, b) after quenching from 800°C; c, d) after quenching from 825°C

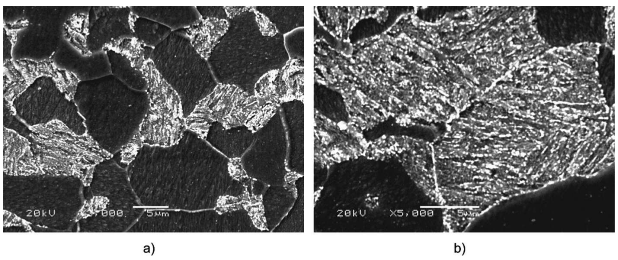

Fig. 4. SEM microstructure of the steel after quenching from 725°C and tempering at 650°C, sample etched in 4% HNO_3

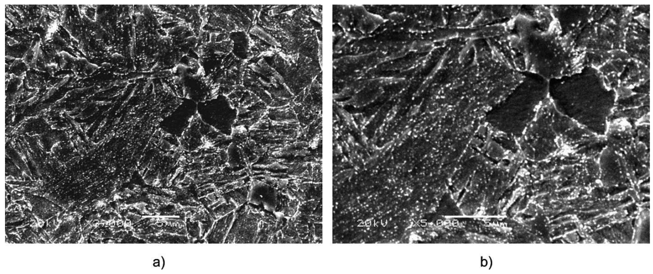

Fig. 5. SEM microstructure of the steel after quenching from 800°C and tempering at 650°C, sample etched in 4%HNO_3

The stereological analysis included an assessment of the content of ferritic phase in the microstructure and gave the opportunity to estimate the content of remaining martensitic phase. The volume fraction of martensite, depending on the temperature was shown in Figure 6. Raising the temperature of the incomplete hardening resulted in increase the volume fraction of martensite. After hardening at 700°C the content of martensitic phase was about 25% as shown Fig. 6. Then increase of temperature up to 800°C caused almost linear growth of martensite up to 92%.

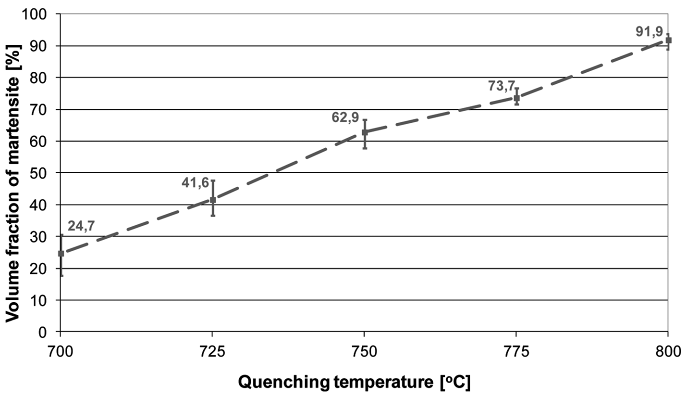

Fig. 6. The influence of quenching temperature on the martensite volume fraction in the steel

The results of the mechanical properties obtained for the samples after each type of heat treatment were presented in graphical form in Figs. 7-12. For quenched samples there was almost twice increase of yield and tensile strength in comparison to as received condition. Systematic increase of yield strength up to 900 MPa and tensile strength over 1200 MPa were observed with increasing volume fraction of martensite. In the case of steel subjected to tempering treatment, the growth of mechanical properties was slightly weaker in nature. The maximum obtained strength yield values were over 600 MPa and tensile strength over 700 MPa. In addition the increase of the mechanical properties with growth of quenching temperature was observed (Fig. 7 and 8).

The changes in the elongation of the DP steel samples compared to the in the delivery state also were noticed. In the case of the quenched samples elongation decreased to 12% and for the additionally tempered samples to the range of 20-25% (Fig. 9).

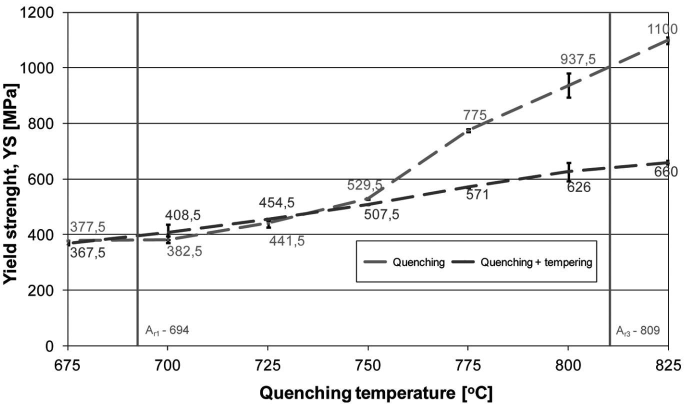

Fig. 7. The effect of quenching temperature on yield strength of the steel

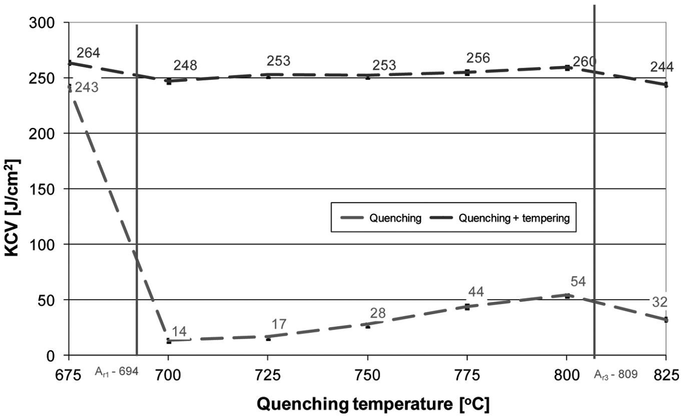

Fig. 10. The effect of quenching temperature on the steel impact toughness

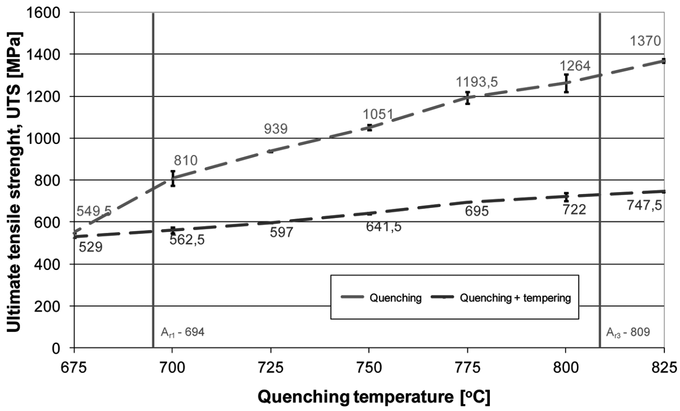

Fig. 8. The effect of quenching temperature on ultimate tensile strength of the steel

The hardness of the quenched steel was more than double higher compared with the samples subjected to additional tempering – Figure 11. In the case of martensite microhardness the relationship was reversed, i.e. the temperature quenching from $\alpha + \gamma$ region caused a decrease in the hardness of this phase (Figure 12), but increase its content increases macrohardness – Figs. 11, 12.

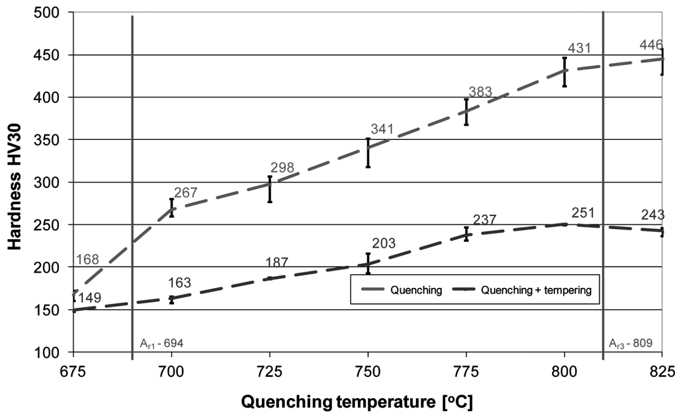

Fig. 11. The effect of quenching temperature on the steel HV hardness

The heat treatment from two-phase range strongly influenced on the impact toughness of the steel (Fig. 10). After heat treatment at 700°C a sharp drop of results to about 14J/cm^2 was observed. Quenching temperature rise affected the steady increase in impact strength up to more than 50J/cm^2. Nearly 25% increase in impact strength was observed in tempered samples compared to as received ones.

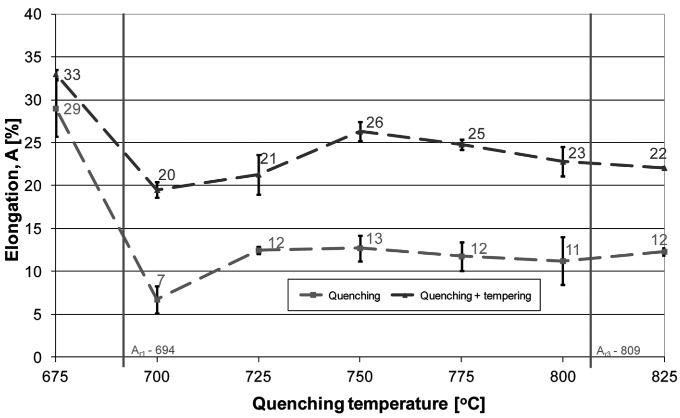

Fig. 9. The effect of quenching temperature on total elongation of the steel

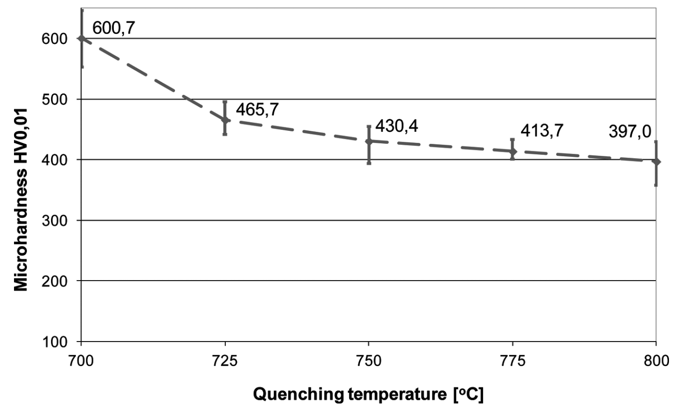

Fig. 12. The effect of quenching temperature on the microhardness of martensite

4. Conclusions

Direct quenching of the steel plate in water from a two region of ferrite and austenite has given rise to the ferritic-martensitic microstructure with a variable morphology. Metallographic and SEM examinations revealed essential differences in the microstructure of the steel depending on the temperature of heat treatment.

After low-temperature quenching from $\alpha + \gamma$ region the observed microstructure consisted mainly of ferritic matrix with dispersed in the interior of grains the small islands of martensitic phase. Increasing the quenching temperature caused almost the linear growth of martensite volume fraction. Also the morphology of martensite changed, which depended on the present in the carbon content. At lower temperatures of quenching the high carbon martensite formed coniferous received character, while the up impoverished in carbon hard phase was characterized by the construction of strip. Similarly, changes in microstructure were noticed for the steel tempered in the place where the structure of tempered martensite was formed as a mixture of ferrite and coagulated cementite.

The results of mechanical properties provided a range of information about the suitability of technology used in steel heat treatment. The results of hardness measurements showed that the increase of quenching temperature caused a gradual increase of steel hardness. In contrary to the additional tempering resulting in the hardness decrease. The relationship for the microhardness of martensite was reversed.

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