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STRUCTURAL CHARACTERIZATION OF Nd:YAG LASER WELDED JOINT OF DUAL PHASE STEEL

CHARAKTERYSTYKA STRUKTURY ZŁĄCZA ZE STALI TYPU DUAL PHASE SPAWANEJ LASEREM Nd:YAG

Fuel economy and, thereby, weight reduction have become a point of considerable interest in the car industry over the past 20 years. The body-in-white, the heaviest and largest car component, comprises about 25-30 percent of the total weight of a medium-sized passengers car. Various new grades of steels with excellent formability have been developed, to meet the automotive industry requirements. The most popular grades of automotive steels are Dual Phase (DP) steels.

In this paper the influence of laser welding technology on the microstructure of welded joint of a dual phase steel is presented. The test joint have been welded under a shielding gas on the stand for robotic Nd:YAG laser welding at the beam power of 2.0 kW and welding speed 2.1 m/min without filler metal.

The microstructure of the 600 MPa DP steel (HDT580X steel) was investigated by means of light microscopy, scanning- and transmission electron microscopy. It was found that the steel exhibits fine grained microstructure consisting of ferrite and martensite – austenite (M-A) islands. Some martensite – bainite (M-B) and martensite – bainite – austenite (M-B-A) islands were also observed. The microstructure of the weld is composed of bainite and lathe martensite. In the Heat Affected Zone (HAZ) the microstructure consists of lathe martensite, bainite and ferrite. The maximum hardness in the HAZ did not exceed 343 HV and the tensile strength of the welded joint (631 MPa) was at the same level as that of the base material (630 MPa).
Keywords: dual phase steel, automobile industry, laser welding, microstructure

Oszczędność paliwa poprzez zmniejszenie masy pojazdu stała się głównym zadaniem, z jakim od ponad 20 lat zmaga się przemysł samochodowy. Karoseria samochodowa stanowi około 25-30 % całkowitej masy pojazdu średniej wielkości. Nowe gatunki stali o dobrej tłoczności są w stanie sprostać wymaganiom, jakie stawia przemysł motoryzacyjny. Do tych stali zaliczają się stale typu Dual Phase (DP).

W pracy przedstawiono wpływ technologii spawania wiązką laserową Nd:YAG na strukturę złącza ze stali typu DP. Na podstawie przeprowadzonych badań za pomocą mikroskopu świetlnego oraz skaningowego i transmisyjnego mikroskopu elektronowego stwierdzono, że badana stal (HDT580X) wykazuje drobnoziarnistą strukturę ferrytyczną z wyspami martenzytyczno – austenitycznymi (M-A). W badanej stali można również zaobserwować obszary wysp martenzytyczno – bainitycznych (M-B) oraz martenzytyczno – bainityczno – austenitycznych (M-B-A). Przeprowadzone badania mikrostruktury ujawniły, że w spoinie złącza występuje struktura bainityczno-martenzytyczna (martenzyt listwowy). W strefie wpływu ciepła mikrostruktura składa się z martenzytu listwowego, bainitu i ferrytu. Maksymalna twardość w obszarze złącza nie przekroczyła wartości 343 HV, a wytrzymałość złącza (631 MPa) była na takim samym poziomie jak materiału rodzimego (630 MPa).

1. Introduction

Over the last decade, a strong competition between steel and low density metal industries has been observed in automotive applications as a result of increasing requirements of passenger safety, vehicle performance and fuel economy. The response of the steel industry to the new challenges is a rapid development of higher strength steels, named Advanced High Strength Steels (AHSS). These steels are characterised by improved formability and crashability in comparison with conventional steel grades. The category of AHSS covers the following steel grades: dual phase (DP), transformation induced plasticity (TRIP), complex phase (CP) and martensitic steels (MART) [1].

The microstructure of the dual phase steel is composed of a soft ferrite matrix and 10-40% of hard martensite or martensite – austenite (M-A) islands [1]. This type of microstructure allows achieving the ultimate tensile strength in the range of 500 – 1200 MPa. Very important for the development of DP steel is the effect of carbon and alloying elements on its microstructure, which was summarized in Table 1.

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TABLE 1

Effect of alloying elements on the microstructure of DP steel [2]

Alloying element	Effect and reason of addition
C (0.06% - 0.15%)	– austenite stabilizer – martensite intensifier – determines the phase distribution
Mn (1.5 - 2.5 %)	– austenite stabilizer – solid solution intensifier of ferrite – retards ferrite formation
Si	– promotes ferritic transformation
Cr, Mo (up to 0.4 %)	– austenite stabilizer – retards pearlite and bainite formation
V (up to 0.06 %)	– austenite stabilizer – precipitation intensifier – refines microstructure
Nb (up to 0.04 %)	– austenite stabilizer – reduces Ms temperature – refines microstructure and promotes ferrite transformation from non-recrystallized austenite

Apart from the chemical composition, microstructure and mechanical properties of automotive steels, the most important factor from the practical point of view is "weldability" of automotive steels [3]. Traditionally, resistance welding and fusion welding have been used in the automotive industry. However, the most prospective welding process in this branch of industry is laser welding. The main advantages of laser welding are small distortions of the sheets caused by a small width of the heat affected zone (HAZ), high welding speed and flexibility of this process. Results of microstructural investigations of DP steel welded joints, reported in the literature, are focused mainly on structural properties of resistance welded joints [4, 5], arc welded [6, 7] and laser welded joints in thicknesses lower than 2 mm [8-10].

Ma at al. [4] indicated that the resistance welded joints in DP600 steel consist mainly of fine martensite islands in the HAZ and coarse islands of lath martensite in the fusion zone. Gupta at al. [5] reported that the microstructure of the weld centre of spot welds in hot rolled low alloy dual phase steel consist of martensite, bainite and acicular ferrite, while the HAZ is composed of tempered martensite. Another welding technology in the automotive industry is the arc welding processes. Kustron at al. [6] examined the microstructure of weld and HAZ in DP600 steel. Resistance welded, MAG and MIG/MAG braze welded joints were investigated. The results showed that the microstructure of the weld and HAZ depends closely on the welding technology and applied parameters. The nugget of the resistance weld is composed of Widmannstätten structure and the HAZ consist of low carbon martensite. Better results were achieved in MAG and MIG/MAG braze welded joints. In these cases martensite was not observed in the weld and HAZ. Previous studies on the weldability of DP 600 steel [7] indicated that the welds of plasma arc and laser beam welded joints contain martensite. However, the volume fraction of those phases and the carbon distribution depends on the thermal cycles experienced. In the case of lower cooling rates during plasma welding, auto-tempering of martensite can take place, which reduces the hardness. Kang at al. [8] reported that the laser weld and HAZ are composed of ferrite and rapidly solidified structure (RSS). TEM examination revealed that the RSS consist of upper bainite, lower bainite and martensite.

However, there is a lack of information on the microstructure of laser welded DP 600 steel joints more than 2 mm in thickness. Therefore in the presented work butt joints 2.4 mm in thickness have been welded by using the Nd:YAG laser, and their microstructure was examined. An effort has been made to study the influence of laser welding on the microstructure of welded joints of Dual Phase steel using light microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

2. Experimental procedure

The dual phase steel HDT580X (acc to. EN 10336:2007 [9]) was used in this study. A summary of chemical composition and mechanical properties is provided in Tables 2 and 3, respectively. The Nd:YAG laser TRUMPF HL 2006D operating at 2 kW was used to weld all specimens at the welding speed of 2.1 m/min. High purity argon was applied for shielding the top surface only, at a flow rate of 16 l/min. The joints were produced by the deep penetration welding method (also known as keyhole welding) without filler metal. Before welding the surface of the specimens was chemically cleaned with acetone. Microstructural examinations were carried out by the light microscope LEICA MEF4M and scanning electron microscope HITACHI S-3500N. The microstructure of the base metal and welded joint was also studied by transmission electron microscopy using JEM-200CX microscope. Welded cross-sections were mechanically ground and polished, and chemically etched with Nital reagent (2% nitric acid – for optical metallography and 3 % – for SEM metallography). Specimens for the TEM analysis were sliced from the cross sections at various locations within and outside the weld zone, ground to 30 μm thickness and finally 3 mm discs were punched. Thin foils were prepared using mechanical dimpling followed by the double jet electropolishing method by means of the Struers Tenupol. To estimate the grain size, the image analysis was performed. The Vickers microhardness measurement across the weld and the base metal was carried out on metallographic specimens at a load of 500 G. During microhardness testing the indentations were randomly distributed without marking the specific phases. However, in case of welded specimens, specific attention was paid to the location of indentations in the region of HAZ and weld. Hardness measurements of the welded sheets were performed using the Zwick hardness tester.

The tensile tests of the base metal (acc. to EN 10002-1 [11]) as well as of the welded joints (acc. to EN 895 [10]) on specimens cut off perpendicular to the joint axis, were performed at room temperature using the mechanical universal testing machine INSTRON 4210. The average value was taken from the results achieved for three specimens.

TABLE 2

Chemical composition (wt %) of HDT580X steel [12]

C	Mn	Si	P	S	Cu	Cr	Ni
0.07	0.90	0.09	0.028	0.001	0.04	0.40	0.04
Mo	V	Al	N	Nb	Ti	B	Sn
0.01	0.004	0.039	0.0058	0.002	0.022	0.0003	0.003

Ito and Bessyo [13] define the carbon equivalent of steels with the carbon content less than 0.18 % as follows:

$$CE = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1)$$

The carbon equivalent of the HDT580X steel is 0.14 %, which indicates that the HDT580X steel exhibits a good weldability.

TABLE 3

Mechanical properties of HDT580X [12]

Property	Specimen orientation to the rolling direction		
	Longitudinal	Transverse	45°
Tensile strength R_m [MPa]	612	630	624
Yield strength R_e [MPa]	420	423	417
Elongation A_{10} [%]	25	22	26

3. Research results

3.1. Base metal

The dual phase microstructure of the base material observed by means of the light microscope is shown in Figure 1. Martensite islands (dark areas) in a ferrite matrix (white areas) are visible on the polished section. On the basis of image analysis the average grain size of ferrite was estimate in the range of 10-15 μm. Due to the fact that in some cases dark areas can be indicated as ferrite, the colour etching by the Beraha reagent has been used to unambiguously identify the martensite phase. Figure 2 shows the effect of colour etching of the base metal, where white areas are martensite and dark areas – ferrite. Gupta at al. [5] have indicated that the microstructure of a dual phase steel can consist of martensite and fine pearlite islands in ferrite matrix or martensite and bainite islands in ferrite matrix. However the small content of carbon in the steel causes that the probability of pearlite presence is very small. More detailed microstructural analysis of the HDT580X steel were performed using SEM. Figure 3 shows the SEM image of the base material microstructure, which is composed of martensite-austenite (M-A) islands in a ferrite matrix. SEM images did not revealed the presence of bainite and pearlite. Therefore TEM analysis was used to confirm the appearance of bainite. Figure 4 shows the microstructure of the HDT580X steel observed on TEM bright field image, composed of martensite-austenite islands in ferrite matrix. In some islands bainite is also present (Fig. 5).

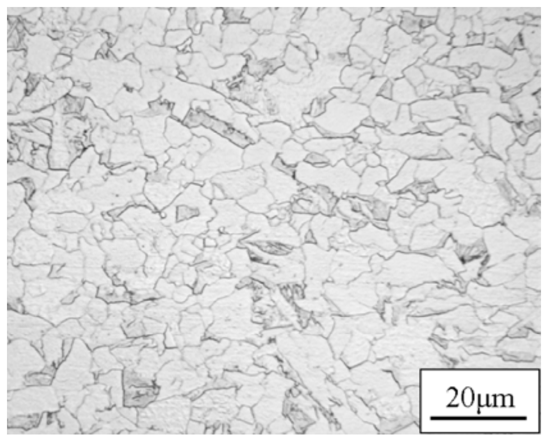

Fig. 1. LM microstructure of HDT580X steel etched with Nital 2% reagent

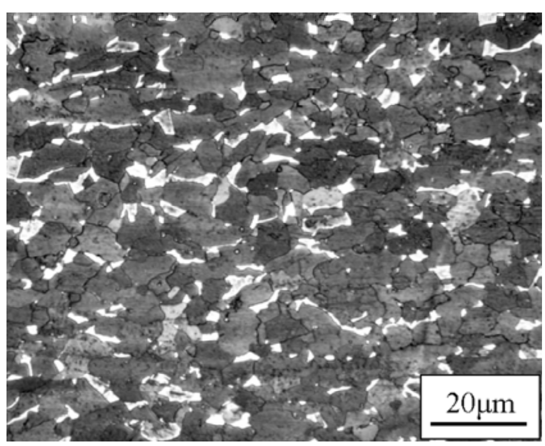

Fig. 2. LM microstructure of HDT580X steel colour etched with Beraha reagent

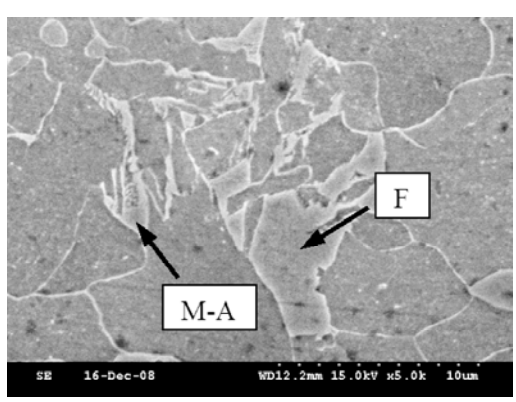

Fig. 3. SEM image of HDT580X steel microstructure etched with 3% Nital, F – ferrite, M-A – martensite – austenite island

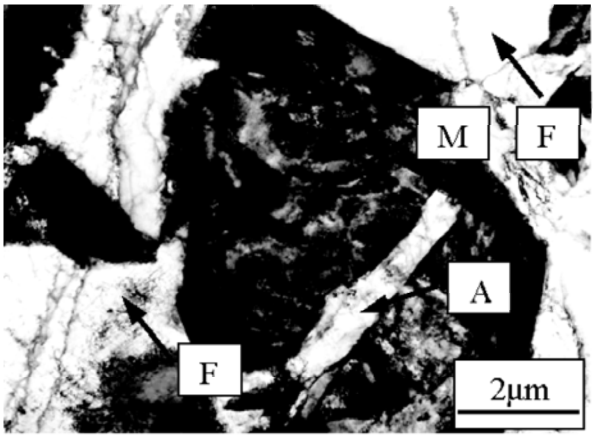

Fig. 4. TEM bright – field image of HDT580X steel microstructure, F – ferrite, M – martensite, A – austenite

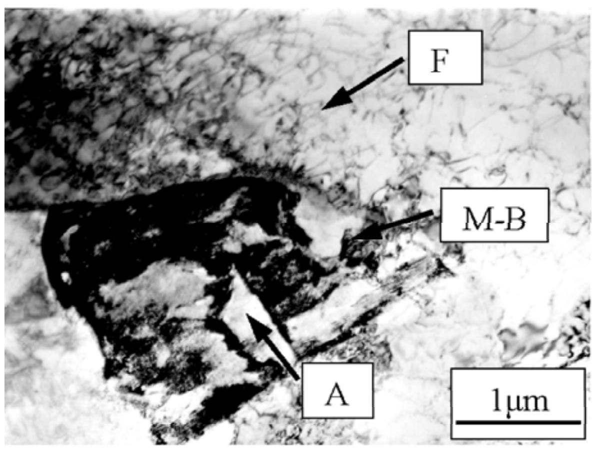

Fig. 5. TEM bright-field image of HDT580X steel microstructure, F – ferrite, M-B – martensite – bainite island, A – austenite

3.2. Macrostructure and microstructures of the welded joint

Figure 6 shows the macrostructure of the laser weld of DP steel. It can be observed that the weld is well formed and free of imperfections, i.e. without porosities or cracks in the fusion zone. The epitaxial crystallisation of the fusion zone initiates on the fusion boundary with the formation of columnar grains, which grew towards the weld centre line.

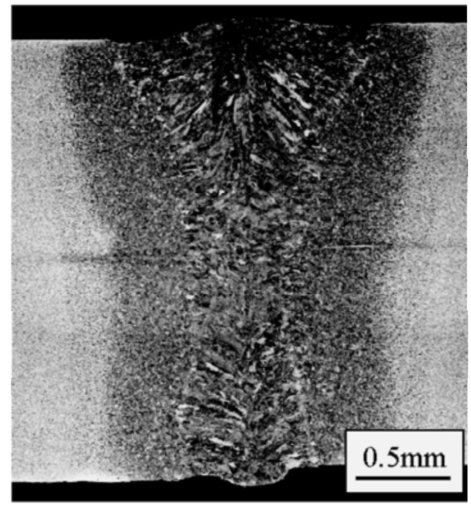

Fig. 6. Macrostructure of the laser welded HDT580X steel joint (2.0 kW, 2.1 m/min) with hardness measurement line marks

To characterize the microstructure of the welded joint, the light microscopy was used. Specimens for microstructural examination were taken from the centre of the weld (Fig 7). Figures 8 and 9 show the microstructure of the weld. The microstructure is uniform and mainly composed of lathe martensite, typical for low carbon steels, achieved at very high cooling rates. However, the light microscopy examination did not allowed to find other structural components. So, the SEM analysis was taken into consideration. Figure 9 shows the results of SEM examination of the weld. The results indicated that the martensite laths are built in packs. The same procedure was taken to determine the microstructure of the HAZ. Figures 10 and 11 show results of light microscopy and SEM examination of the area between HAZ and base material. The microstructure of HAZ is composed of a mixture of bainite, martensite and ferrite.

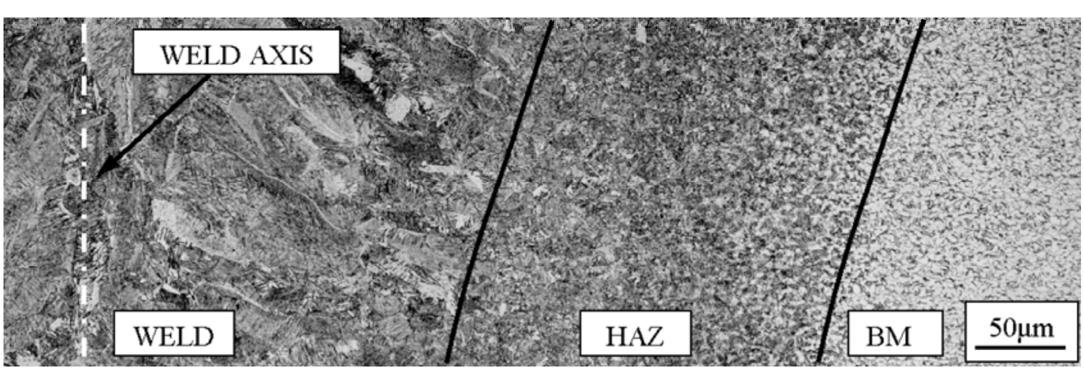

Fig. 7. Light microscopy images of the weld centre, HAZ – Heat Affected Zone, BM – Base Metal

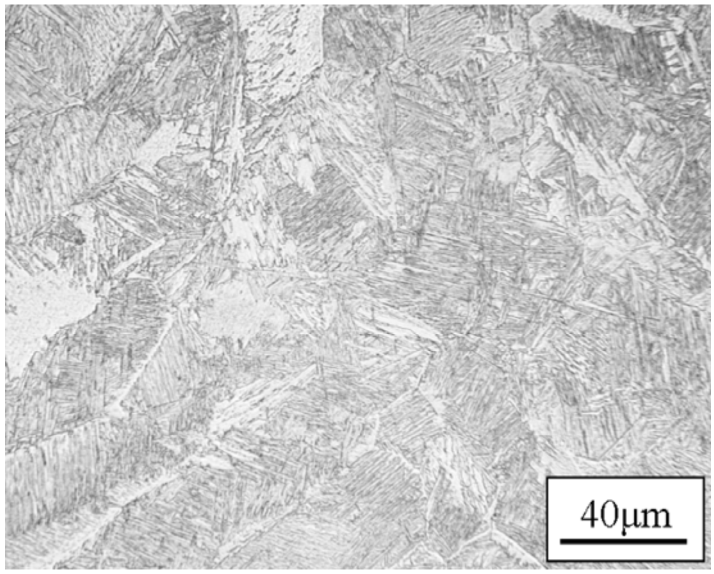

Fig. 8. Light microscopy image of the weld microstructure in the HDT580X steel welded joint

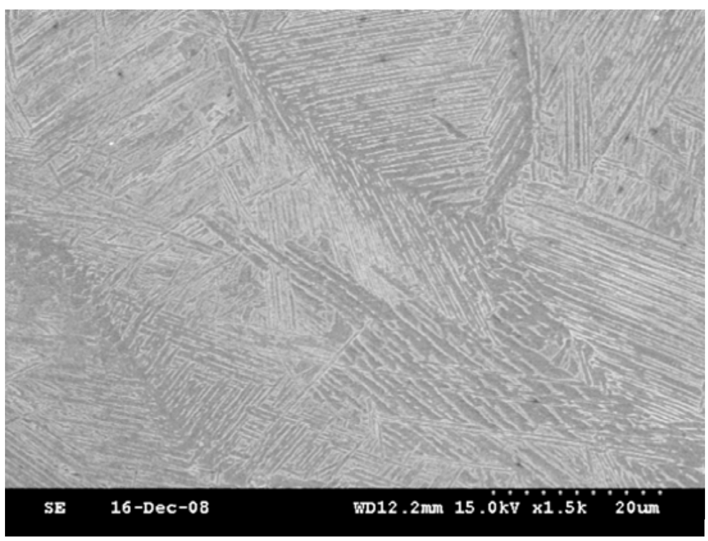

Fig. 9. SEM image of the microstructure of the weld region in the HDT580X steel welded joint

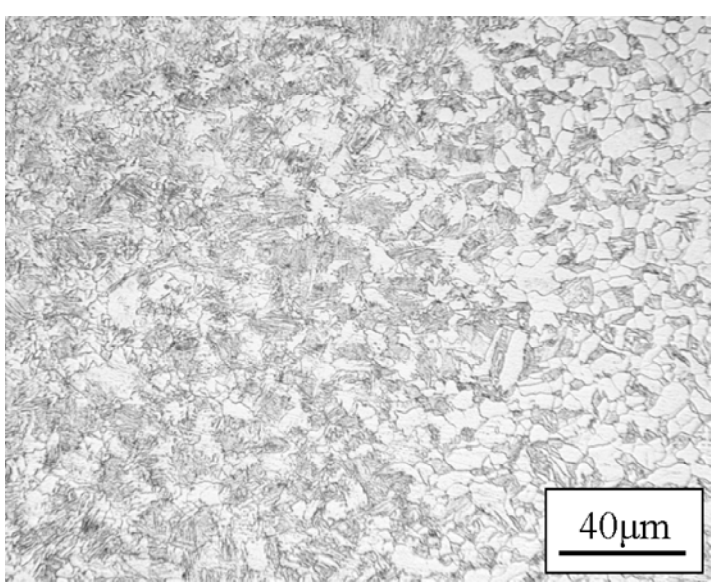

Fig. 10. Light microscopy image of the microstructure of the HAZ in the HDT580X steel welded joint

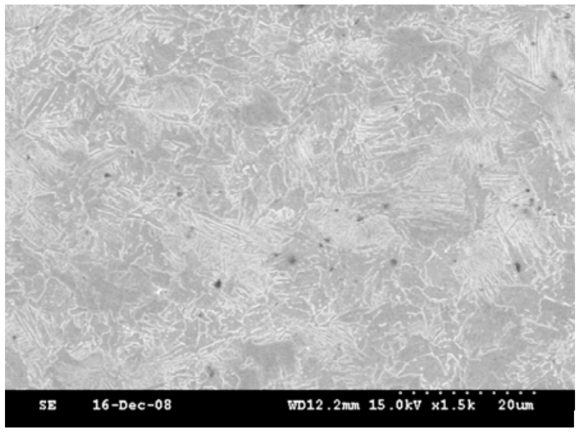

Fig. 11. SEM image of the microstructure of the HAZ in the HDT580X steel welded joint

The analysis of microstructure of the weld and HAZ performed by means of the light microscopy and SEM is rather inaccurate. Therefore, the TEM observations were carried out.

Figures 12 and 13 show the microstructure of weld. The main component of the weld microstructure is the lath martensite. As is seen in Fig. 12, packages of martensite laths are the main microstructural components. Fig. 13 shows the arrangement of martensite laths within the package.

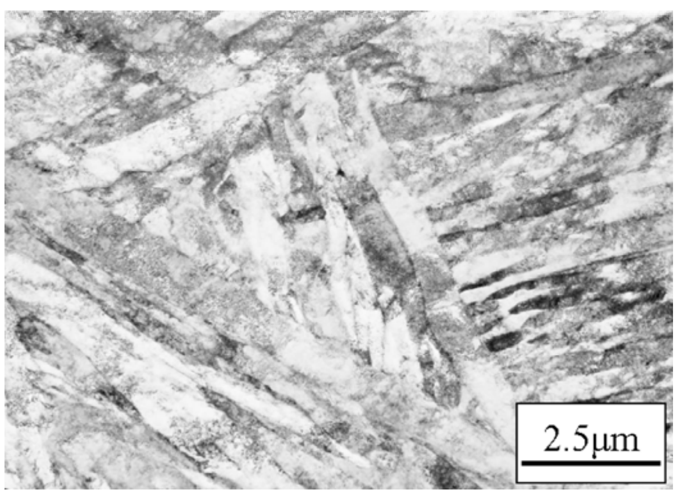

Fig. 12. TEM bright-field image of the weld microstructure

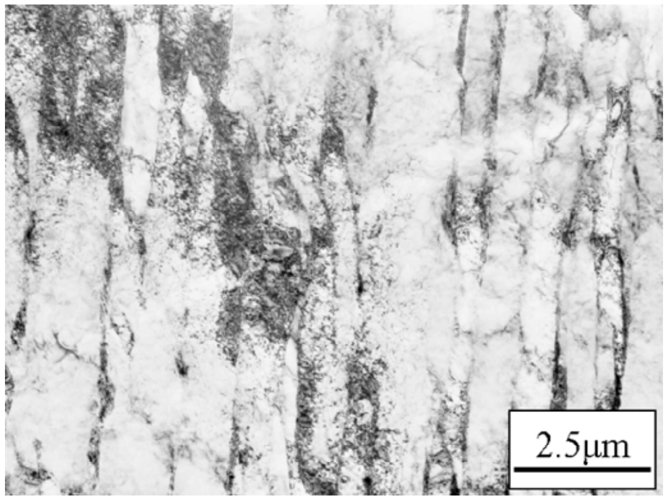

Fig. 13. TEM bright-field image of the weld microstructure

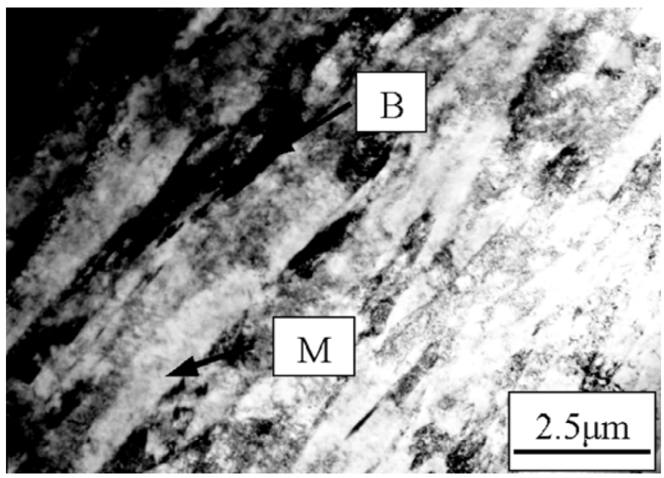

Fig. 14. TEM bright-field image of the HAZ microstructure of the welded joint

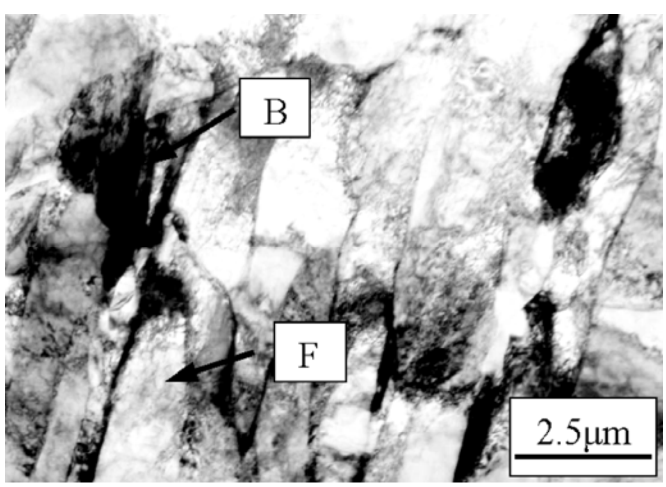

Fig. 15. TEM bright-field image of the HAZ microstructure of the welded joint

Identification of microstructural components was based on the electron diffraction analysis. Figure 16 shows the electron diffraction pattern of the microstructure presented in Figure 13. The strong spots represent martensite with $[\bar{1}\ 1\ \bar{1}]$ zone axis. The diffraction pattern indicates that the dominant orientation of laths is close to the [101] direction.

The domination of one preferred orientation confirms that the laths within martensite packages have a similar crystallographic orientation. The separate spots of retained austenite observed are marked as A in Figure 16. TEM examinations allowed to identify that the HAZ is composed of a mixture of bainite and martensite, as shown in Figure 14. Such microstructure is typical for the fusion line. In the middle of the HAZ the microstructure consists of bainite and ferrite. (Fig. 15). However, it is necessary to notice the fact that it was difficult to observe martensite and bainite islands on TEM images due to their low volume fraction. Martensite exhibited the morphology typical for high carbon steels, because the amount of carbon in the islands was several times higher than the overall content of this element in steel. It was rather difficult to distinguish between martensite and bainite due to their identical crystal structure (body centered cubic).

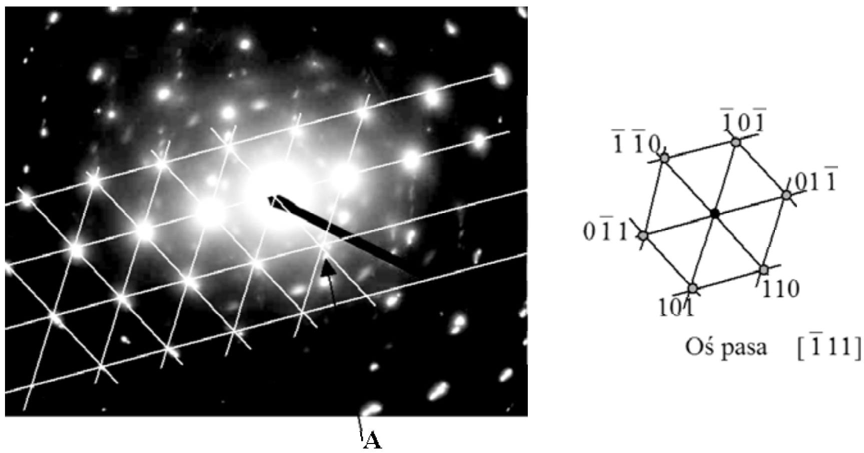

Fig. 16. Selected Area Electron Diffraction (SAED) pattern of martensite and martensite and austenite of the weld shown in Figure 13. [$\bar{1}$ 1 $\bar{1}$] zone axis of martensite

To determine the mechanical properties of the welded joint, microhardness measurements and tensile test were carried out. The changes of hardness across the weld in the cross sectional plane of the laser welded joint are shown in Figure 17. The base material hardness values did not exceed 226 HV. In the HAZ an increase of hardness to 285 HV was detected. The maximum hardness of 343 HV was observed in the weld. These results confirmed that the low carbon lath martensite was present in the weld and HAZ.

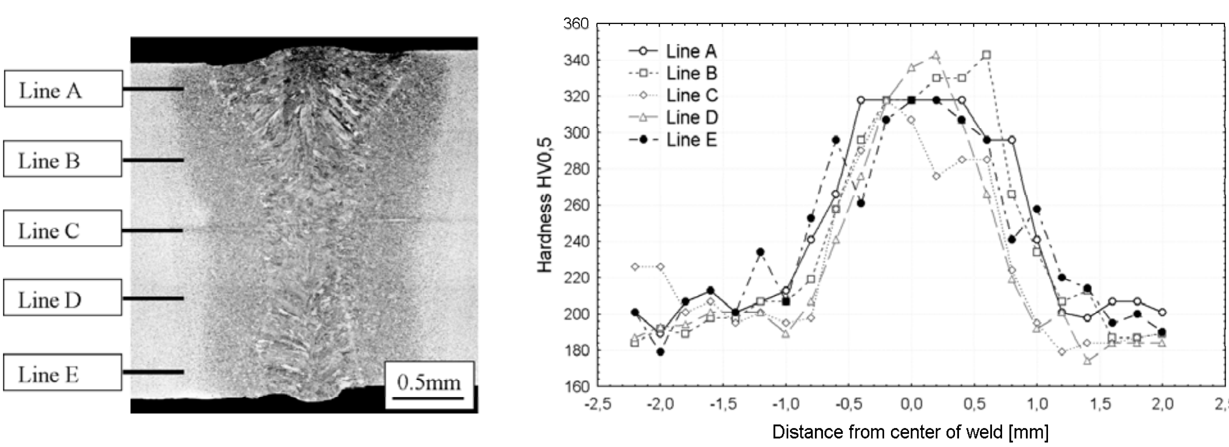

Fig. 17. Microhardness distribution across the welded joint

The tensile test revealed that the strength of welded joints is at the same level as that of the base material and equals R_m= 631 MPa (average value for three specimens). All three specimens tensile tested ruptured in the base material away from the weld. These results indicate that the strength of welded joints is not lower that of the base material (630 MPa).

4. Discussion of results

The microstructure of the Dual Phase steel has been investigated using light microscopy (Figures 1 and 2), scanning electron microscopy (Fig. 3) and transmission electron microscopy (Figs. 4 and 5). The results show that the microstructure of the HDT580X steel is composed of a soft ferrite matrix with hard martensite - austenite islands. However, in some cases bainite was also observed. The overall chemical composition (carbon content of 0.07 %) of this steel does not allow the formation of pearlite. The detailed analysis of the welded joints microstructure indicates that it is composed of lath martensite built in packages. These packages are aligned mainly perpendicular to the heat flow direction. However, in same cases, as shown in Figures 12 and 13, these packages have a random orientations. The way of crystallization of the weld metal is shown in Figures 6 and 7. The HAZ of the laser welded joint consists of the mixture of ferrite, bainite and martensite, depending on the distance from the weld axis. Figures 10, 11, 14 and 15 show the results of structural examination of the HAZ by light microscopy, SEM and TEM, respectively. Furthermore, in contrast to previous studies [7], results of the present investigations indicate that the hardness of the HAZ does not exceed 343 HV. This is due to the low carbon content of the lath martensite.

Concluding the results achieved, it can be pointed out, that microstructural examinations of welds revealed that the Nd:YAG laser welding is a useful technology for joining HDT 580X steel sheets.

5. Conclusions

On the basis of metallographic examination, hardness measurements and mechanical tests of the base material and welded joints the following conclusions can be drawn:

- the microstructure of the HDT580X steel is composed of martensite-austenite islands in ferrite matrix, in some islands bainite was also observed;
- low carbon equivalent indicates that the HDT580X steel can be characterized by good weldability;
- the macrostructural examination of the weld cross sections revealed, that the welded joints were free of any defects, such as porosity, concavity, voids, inclusions or misalignment. This indicates that the applied laser welding parameters are appropriate to obtain sound welds;
- the microstructure of the weld metal is composed of lath martensite, while the HAZ consists of a mixture of ferrite, bainite and lath martensite. The maximum hardness does not exceed 343 HV;
- the tensile strength of welded joints (R_m= 631 MPa) is at the same level as that of the base material.

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