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The Effect of Cutting Techniques on the Structure and Properties of Low-Alloy Martensitic Steels

Abstract: The paper analyses the effect of cutting techniques on the structure and properties of low-alloy martensitic steels. Tests involved steels characterised by increased abrasive wear resistance. The test steels were provided by four steel manufacturers. The cutting process was performed using a gas torch, plasma, abrasive waterjet and a band saw. The research work included hardness measurements of plates in the pre-treatment state, the distribution of hardness in the cut zone, measurements of surface roughness after cutting as well as metallographic tests of the base material (BM) and the heat affected zone (HAZ). The cutting method significantly affected the operational properties of abrasion-resistant steels. In terms of the surface quality, the most favourable results were obtained using the plasma cutting process, which was confirmed by related measurements of surface roughness. The cutting process involving the use of gas torches and plasma led to the deterioration of the mechanical properties of the steel in the cut zone. The aforesaid result could be ascribed to the formation of the HAZ in this area, the morphology of which was similar to the HAZ formed during the welding process. The hardness measurements and metallographic tests concerning the cut zone revealed a significant decrease in steel hardness, resulting from heat-triggered structural changes.

Keywords: cutting techniques, hardened steels, structure and properties in the cut zone

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Introduction

Increasingly high requirements concerning the quality of elements combined with the increasingly high complexity of these elements and pursuit of reducing both time and costs in the production process necessitate the search for and development of superior machinery and manufacturing methods. However, the continuous optimisation of processing parameters and striving for their lowest effect on the structure of materials subjected to processing should not compromise the economic aspect of production.

Low-alloy martensitic steels are modern ferroalloys characterised by high abrasive wear resistance, good weldability, favourable mechanical properties and high resistance to impact loads [1]. Good mechanical properties,

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workability and possibility of joining by means of conventional methods enable the application of manganese abrasion-resistant steels in numerous industries. The above-named steels are usually used in the production of expendable elements of concrete mixers, feeders, funnels, silos, systems for the transport of aggregates and ores, work edges of building machinery, expendable parts of mining machines, housings, scoops, platform structures, tipper truck bodies etc. [2]. In the production process, plates made of abrasion-resistant steel grades are hardened in cross-section, where the minimum hardness of the core constitutes 90% of the minimum guaranteed surface hardness. Abrasion-resistant steels are characterised by the fine-grained structure in the normalised state, high mechanical properties and high abrasive wear resistance [1]. However, the aforesaid steels may lose their properties if affected by temperature exceeding 200°C–250°C.

The application of various procedures and operations when processing structural materials may significantly affect the structure and properties of elements subjected to treatment. A significant challenge is posed by the cutting process itself as the selection of an appropriate technique is very important in terms of the intended use and the further processing of a given material. Cutting is usually the first operation as regards product fabrication-related technologies. Technologically advanced cutting techniques, including plasma, laser [4], spark erosion and waterjet cutting [5, 6] provide many treatment-related possibilities. CNC machines and specialist software programmes makes the process of cutting precise and fully automated. The above-named machines, in conjunction with their control systems, provide both high precision and repeatability when cutting even very complicated elements. As a result, additional treatment is often unnecessary and production costs are, consequently, lower [7].

Test materials

The tests involved abrasion-resistant steel grades provided by four manufacturers, ranging the most expensive (offered by leading producers) to significantly cheaper. In all of the cases, the manufacturers guaranteed hardness restricted within the range of 450 HBW to 530 HBW. Table 1 presents the chemical composition of the test steel grades, whereas Table 2 presents their mechanical properties.

Table 1. Comparison of the chemical composition of the test abrasion-resistant steels

Material	Contents of chemical elements [max %]								
	C	Si	Mn	P	S	Cr	Ni	Mo	B
1	0.30	0.70	1.60	0.020	0.010	1.50	1.50	0.60	0.005
2	0.30	0.70	1.70	0.030	0.0115	1.50	0.80	0.50	0.004
3	0.28	0.45	1.50	0.025	0.010	1.00	0.6	0.40	-
4	0.38	0.7	1.7	0.020	0.010	1.20	1.0	0.65	-

Table 2. Comparison of mechanical properties of abrasion-resistant steel grades

Material	Guaranteed properties					
	Hardness HB Min	Yield point R_e	Toughness J	Ultimate strength R_m	Ultimate ductility A[%]	Plate thickness [mm]
1	470	1400	37	1550	8	2-100
2	470	1250	25	1600	8	5-60
3	450	1000	-	1200	7	3-60
4	470	1250	-	1600	8	8-80

All of the steel grades can be subjected to welding, plastic working or mechanical working, provided that related manufacturer's instructions are strictly complied with. The steel grades can also be subjected to cutting performed using each of the available techniques.

Specimen preparation

All of the 10 mm thick test plates were sampled for specimens having dimensions 120 mm × 120 mm. Each plate was cut using another technique (propane, plasma, waterjet, band saw).

The cutting process was performed on stations equipped with a CNC CUTTER II cutter (3.0 m × 2.0 m) provided with a Messer gas cutting torch (100 mm) (Fig. 1a) or a Hypertherm Powermax105 plasma cutter (Fig. 1b), a waterjet (Tech Jet) (3500 bar) (Fig. 1c) and a band saw (Bomar) (Fig. 1d).

All cutting operations were performed using optimum parameters related to a given material thickness. In terms of plasma cutting, the cutting rate amounted to 2790 mm/min, whereas the voltage amounted to 145 V. As regards propane cutting, the cutting rate amounted to 630 mm/min, the pressure of heating oxygen amounted to 0.25 MPa and the pressure of cutting oxygen amounted to 0.6 MPa. In terms of abrasive waterjet cutting, the cutting rate amounted to 60mm/min, the pressure of water amounted to 280 MPa and the diameter of abrasive grit amounted to 0.212 mm. The cutting process was directly followed by temperature measurements performed approximately 5 mm away from the specimen edge. In terms of propane cutting, temperature was restricted within the range of 370°C to 450°C. As regards plasma cutting, temperature measured in the same conditions amounted to approximately 79°C. In terms of abrasive waterjet cutting and cutting with the band saw the temperature of the edge after cutting was slightly higher than ambient temperature and amounted to approximately 30°C.

Testing techniques and test results

Hardness measurements

The primary parameter enabling the determination of the mechanical properties of the material and the effect of technological processes on these properties is hardness. Hardness measurements were performed using the Brinell hardness test, a Zwick/Roell ZHV10 hardness tester, an indenter with a ball having a diameter of 1 mm and a load of 294.2 N (30 kg). The indent diameter was measured at a magnification of 200x. Before the measurement, the surface of the specimens was subjected to manual grinding performed using abrasive paper having a grit size graded from 40 to 150.

The first stage involved the determination of the mean hardness of the test plates. To this end, it was necessary to perform 5 measurements in

Fig. 1. Techniques used for the cutting of 10 mm thick plates: a) gas cutting with the gas torch, b) plasma cutting, c) abrasive waterjet cutting and d) band saw cutting

the centre of the specimen. Figure 2 presents the comparison of the mean hardness values (outside the cut area) of the test materials in relation to the minimum hardness values declared by the manufacturers. The test results revealed that the hardness of specimens nos. 1 and 2, i.e. 493 HB and 455 HB respectively, exceeded the minimum declared value of 450 HB. The remaining specimens were characterised by hardness values lower than the values declared by the manufacturers.

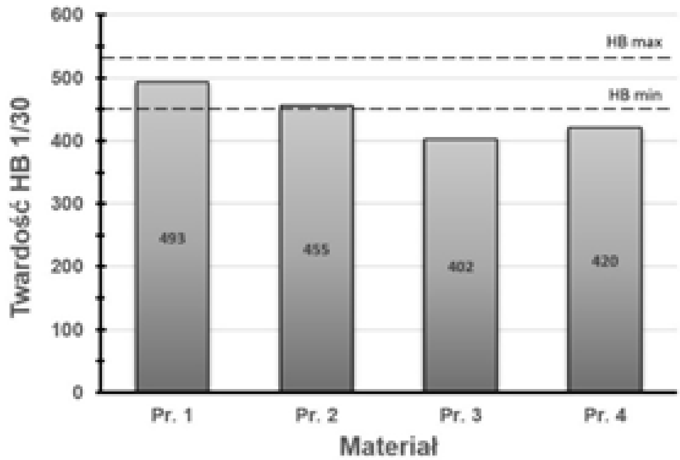


Fig. 2. Comparison of the mean hardness of the test materials with the hardness declared by the manufacturers

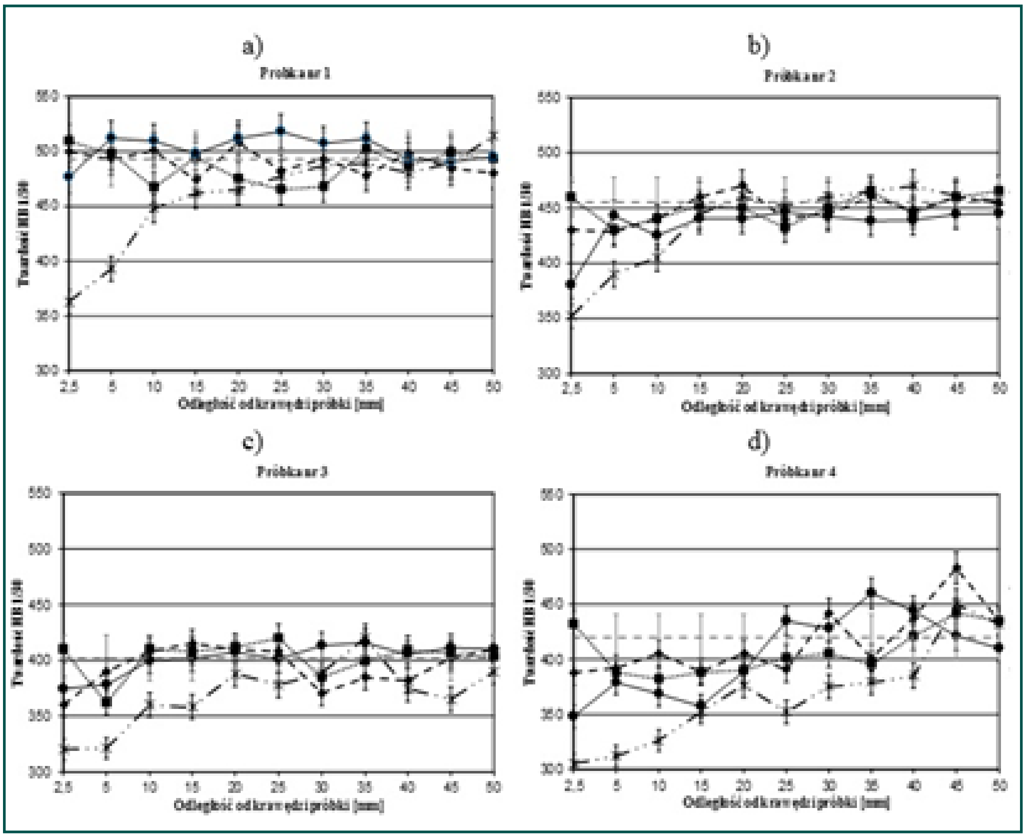


Fig. 3. Distribution of hardness after cutting with various cutting methods, in relation to : a) specimen no. 1, b) specimen no. 2, c) specimen no. 3 and d) specimen no. 4

The subsequent stage involved the performance of hardness distribution in the cut zone in accordance with a related measurement scheme, where the first measurement point was located 2.5 mm away from the specimen edge, the next measurement point was located 5 mm away from the first measurement point and subsequent points were located every 5 mm towards the centre of the specimen (50 mm from the edge). The results related to individual specimens are presented in Figure 3a–d.

The test results revealed that, in all of the cases, the highest changes in hardness in the cut zone were observed after cutting with the gas torch and with plasma. As regards cutting with the gas torch, the greatest decrease in hardness was observed in specimen no. 4 (a decrease of 30% in relation to the hardness of the material). In turn, as regards specimens nos. 1–3, a decrease in hardness was restricted within the range of approximately 20% to 25% in relation to the mean hardness value outside the cut zone.

Smaller differences were observed in terms of plasma cutting. In relation to specimens nos. 2 and 4, a decrease in hardness in relation to the mean hardness value measured outside the cut zone amounted to approximately 20%. The most favourable results were obtained in relation to specimens nos. 1 and 4, where the maximum hardness decrease amounted to 3% and 7% respectively (in relation to the mean hardness value measured outside the cut zone). In all of the cases the greatest decrease in the HAZ hardness was observed in the edge cut with propane.

Surface roughness measurements after cutting

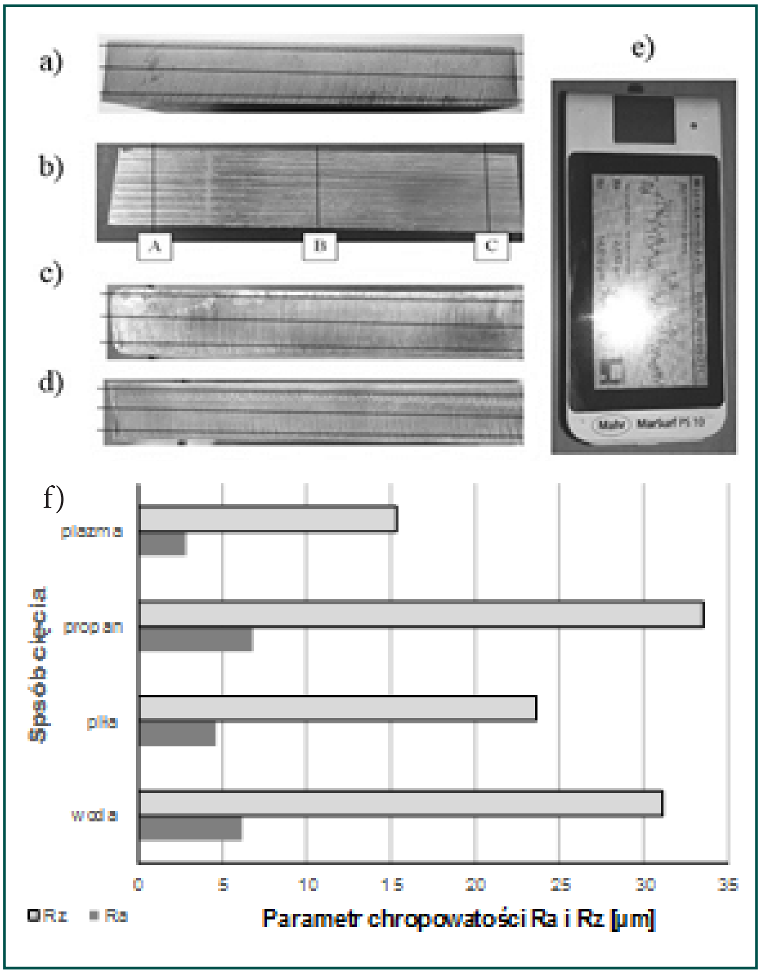
In relation to all of the cutting techniques, surface roughness measurements were performed in the 2D system, using a Mahr PS10 contact profile measurement gauge provided with a PHT350 head (Fig. 4e).

The macroscopic observations revealed that differences in surface quality after cutting were primarily related to the cutting technique and did not depend on the steel grade. For this reason, 2D roughness measurements were performed for a selected specimen, i.e. specimen no. 1. The measurements were performed in relation to each of the four edges subjected to cutting with different techniques (waterjet, band saw, gas torch and plasma). The roughness measurements were performed perpendicular to the cut line at the following distances: 2 mm from the upper cut edge – line A, in the middle of the cut surface – line B and 2 mm from the bottom cut edge – line C. The adopted measurement section amounted to 4.8 mm, whereas the run-in and the run-out of the profile measurement system needle amounted to 0.8 mm. Figure 4 a–d presents the edges after cutting performed using each of the cutting techniques, with 2D roughness measurement areas (lines A, B and C). Roughness profile measurements were performed for each surface and in relation to each cutting technique. The profile measurements included the mean arithmetic deviation of the roughness profile (Ra), roughness height according to ten profile points (Rz), the highest profile rise (Rp), the deepest profile cavity (Rv) and the total height of the profile within the measurement section (Rt) [8]. The results concerning the surface after being subjected to waterjet, band saw, propane and plasma cutting are presented in Table 3.

The analysis of the results, particularly parameters Ra and Rz, revealed that the best surface quality was obtained after cutting with plasma, where parameters Ra and Rz amounted to 2.3 µm and 15.3 µm respectively. The highest value was obtained in the middle part of the cross-section (line B). The results recorded at the entrance and exit (line A and C) were similar (Table 3 and Fig. 4f). Higher roughness parameter values were obtained in relation to cutting with the band saw, i.e. Ra = 4.6 µm and Rz = 23.65 µm. In the above-named case, the values were similar across the entire cross-section

Table 3. Roughness parameter values in relation to various cutting techniques

Parameter [µm]	Cutting technique			
	waterjet	band saw	propane	plasma
Ra	6.195	4.614	6.800	2.861
Rz	31.157	23.651	33.556	15.317
Rp	15.896	11.396	16.771	7.481
Rv	15.260	12.255	16.785	7.835
Rt	38.186	28.334	50.854	19.404



of the specimen. The highest roughness parameters were obtained in relation to waterjet cutting and cutting with the gas torch, where parameter Ra exceeded 6 μm and parameter Rz exceeded 30 μm. The results are compared in Figure 4f.

Metallographic tests

Specimens used in the metallographic tests were sampled from each steel grade and each four edges cut using various methods. The specimens were cut out using a CM-15 disc cutter (LECO) and discs (Struers) for the cutting of ferroalloys characterised by hardness restricted within the range of 500 HV to 800 HV. During cutting, the specimens were intensively cooled with water. After cutting, the specimens were included in a thermosetting mix using a PB-15 press (LECO). Next, the specimens were subjected to manual grinding involving the use of abrasive paper having a grit size graded from P350 to P1500. The grinding process was performed until the obtainment of the flat and smooth surface. Afterwards, the specimens were subjected to mechanical polishing performed using a grinder/polisher (LECO) and a polishing wheel with synthetic fibres. The polishing process was performed until the removal of scratches visible under the microscope. The polishing process involved the use of the aqueous slurry of Al_2O_3. Afterwards, the specimens were subjected to etching in the solution of ethyl alcohol and nitric acid (Nital). The metallographic tests of the specimens were focused on the base material (BM) and the heat affected zone (HAZ). The tests were performed in relation to each of the four steel grades and in relation to each cutting technique. The microstructural tests were performed using an OLYMPUS IX70 optical microscope and a magnification of 50x, 200x and 500x. The photographs of the structures were taken using an OPTA-TECH camera and an OPTA-View image analysis software programme.

In the as-received state, high-quality abrasion-resistant steels are normalised. Their structures contain grains of ferrite and of pearlite with fine-lamellar cementite. Afterwards, the above-named steels are hardened in water and, depending on their grade and thickness, tempered at a temperature restricted within the range of 200°C to 700°C. The metallographic tests of all of the steel grades subjected to analysis revealed that, before cutting, their structure was composed of tempered martensite with retained austenite. Figure 5 presents exemplary structures of steel no. 1 (Fig. 5a) and steel no. 2 (Fig. 5b).

The determination of the effect of the cutting technique on structural changes required the performance of microstructural tests. Figure 6 presents the structures of selected steel grades (specimen 1 and specimen 3) in the area subjected to cutting with the band saw (Fig. 6 a, c) and waterjet (Fig. 6 b, d).

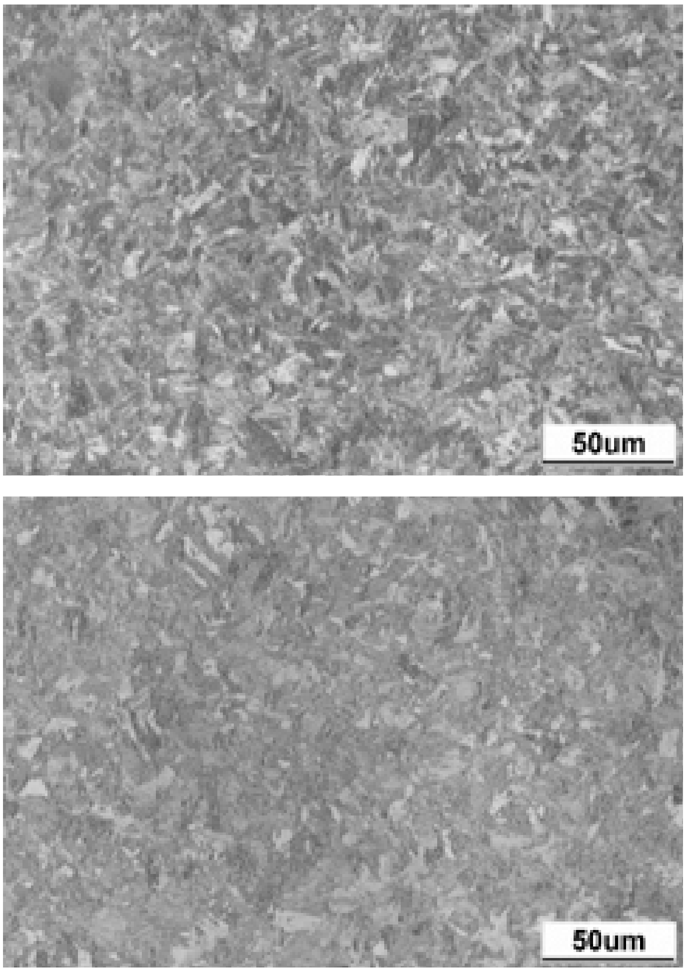


Fig. 5. Microstructure of abrasion-resistant steel a) specimen no. 1, b) specimen no. 2; mag. 500x

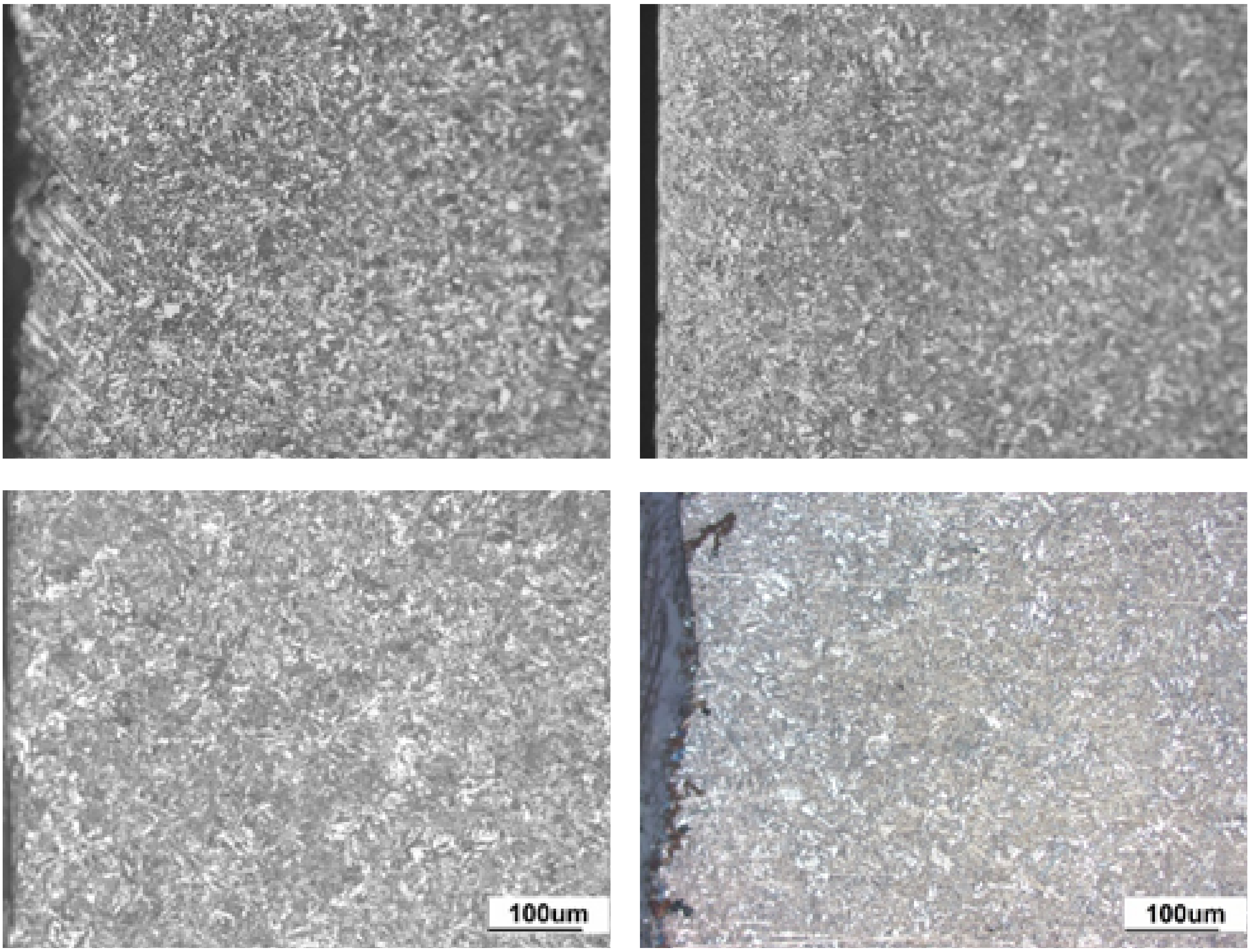


Fig. 6. Microstructure of the specimen: steel no. 1 after a) cutting with the band saw and b) waterjet cutting; steel no. 3 after c) cutting with the band saw and d) waterjet cutting; mag. 200x

The analysis of structural images revealed that the cutting technique did not affect the structure of the steel grades subjected to cutting by means of the least invasive techniques (i.e. using waterjet and the band saw). The structure of the zone adjacent to the cut surface contained tempered martensite and retained austenite, i.e. the same as the one present in the steels before the cutting process.

In cases of cutting involving the use of high-power techniques, i.e. a gas torch or plasma, the metallographic tests revealed the variable width of the heat affected zone (related to the cutting method). The microstructural changes in the HAZ result from phase transformations and deformations of the crystallographic lattice. The heating of the metals and alloys above a certain temperature characteristic of them resulted in the related grain growth, i.e. coarse-grained martensite (area A). Next, it was possible to observe fine-grained tempered martensite (area B) and the normalised area followed by the area characteristic of the base material (area C). The above-named structural transformations were observed in all of the cases subjected to analysis. Exemplary structures are presented in Fig. 7 a–d. The structural changes in the cut zone were confirmed by hardness measurements presented in Fig. 3 a–d.

Figure 7 presents the effect of cutting on the width of the HAZ. The widest heat affected zone was formed as a result of cutting with the gas torch (propane), where the HAZ width amounted from 968 μm in relation to steel no. 1 (Fig. 7a) to approximately 1207 μm in relation to steel no.3. In the remaining cases, i.e. in relation to steel no. 2 (Fig. 7c) and steel no. 4, the HAZ width amounted to 1070 μm and 1126 μm respectively. Cutting with plasma resulted in the formation of the narrower heat affected zone, amounting to approximately 500 µm in relation to steel no. 1 (Fig. 7 b) and 737 µm in relation to steel no. 2 (Fig. 7d). In relation to steel no. 3 and steel no. 4, the HAZ width amounted to 661 µm and 546 µm respectively. The lowest effect of cutting on the HAZ width (regardless of the applied cutting technique) was observed in steel no. 1, i.e. the steel satisfying the requirements specified in the standard. Figure 8 presents the comparison of HAZ width values in relation to the cutting method.

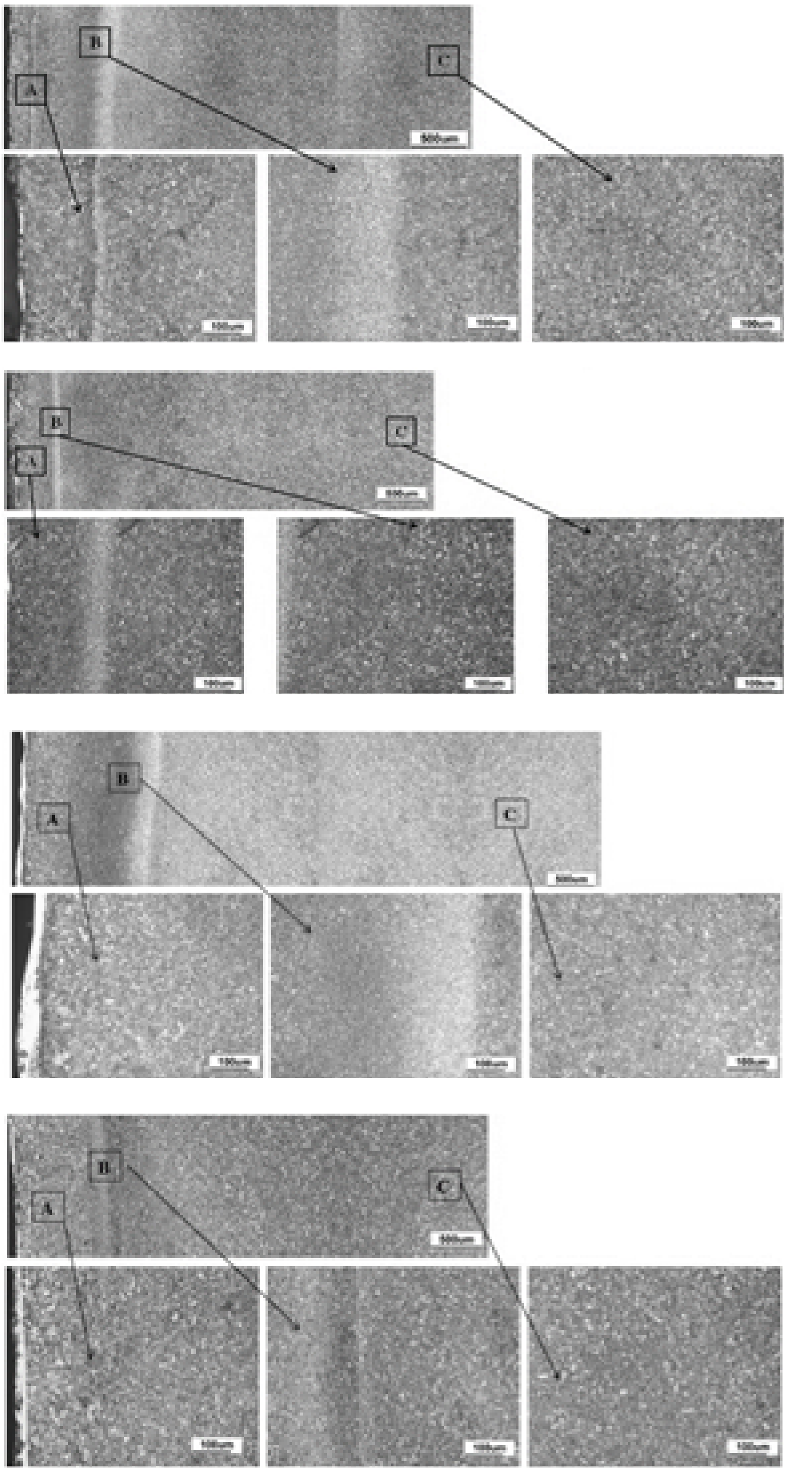


Fig. 7. Microstructure of materials no. 1 and 2 after: a) and c) cutting with the gas torch (propane) and b) and d) cutting with plasma; the subsurface structure, in the HAZ, outside the cut area (areas A, B and C); mag. 50x and 200x

Conclusions

The above-presented tests enabled the formulation of the conclusions presented below.

1. The hardness measurements revealed that the quality of abrasion-resistant steels was related to a given manufacturer. Only two of the steel grades subjected to analysis satisfied minimum hardness-related requirements (specimen 1 and 2). The remaining specimens failed to achieve the required hardness value.
2. The operational properties of abrasion-resistant steels are significantly affected by the cutting method. Nearly all of the aforesaid steels can be cut using all available techniques, yet the most favourable results (high hardness across the entire cross-section and the lack of structural changes) were obtained when cutting was performed using the waterjet and the band saw.
3. Cutting with gas torches and plasma led to the deterioration of mechanical properties in the cut zone. The above-named result was related to the formation of the HAZ characterised by the morphology similar to that of the HAZ formed during welding. The steel hardness in the cut zone decreased significantly, which was the result of structural changes triggered by heat.
4. The width of the HAZ depended on the cutting technique, and particularly on a heat input to the material in time.
5. The tests concerning the quality of the surface after cutting revealed that the lowest parameters Ra and Rz were obtained in relation

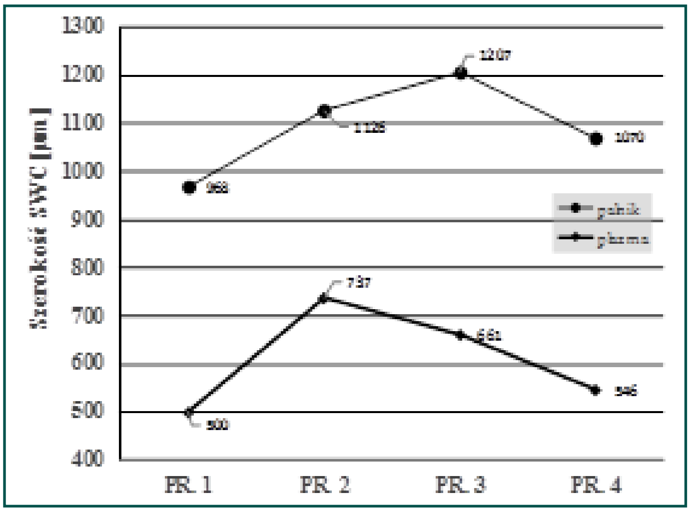


Fig. 8. Width of the heat affected zone (HAZ) in relation to the cutting method

to plasma cutting, whereas the highest parameters Ra and Rz were obtained in relation to cutting performed with the gas torch.

6. The structure of the abrasion-resistant steels was composed of tempered martensite with retained austenite. However, the cutting process performed using high-power techniques resulted in the significant growth of martensitic grains and the significant tempering of martensite in the cut zone, leading to a significant decrease in hardness in this area.

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