Marek St. Węglowski, Tomasz Pfeifer

Influence of a cutting technology on the quality of unalloyed steel surface

Abstract: The article presents requirements concerning quality after cutting in accordance with the requirements of PN-EN 1090-1+A1:2012P and PN-EN ISO 9013:2008 standards as well as the results of surface tests after cutting with a laser beam, plasma, oxygen and water stream. The test results reveal the significant influence of the cutting technology on surface quality. The research related quality tests involved the measurements of perpendicularity, hardness, profile height and metallographic examination. The lowest hardness was achieved by water cutting, whereas the highest was obtained by plasma cutting under the water surface. The lowest porosity was achieved by means of plasma cutting over the water surface, whereas the highest by laser beam cutting. The lowest perpendicularity tolerance was obtained by plasma cutting under the water surface (1.6 m/min), whilst the highest was achieved by laser beam cutting and HD plasma.

Keywords: steel cutting technologies, cutting quality, surface after cutting;

Introduction

Cutting technologies are commonly used for cutting various elements out of sheets as both "finished products" as well as those intended for further processing. Cutting technologies are also used for cutting shapes and making openings. Usually, the geometry of cut out elements is complex. The range of cutting method applications also includes pre-weld edge preparation (bevelling) to obtain a weld groove of appropriate geometry. However, it is necessary to verify the usability of a given cutting technology in view of meeting specific requirements.

Cutting can be manual, mechanised, automatic or carried out on robotic stations. Cutting (bevelling) can be conducted on a plane or in space [1], particularly if it is necessary to prepare for welding closed shapes, i.e. pipes and beams or for cutting inner openings in pipes or shapes with closed cross-sections. Such elements are used in the production of tanks (jacket – port) or structural joints in steel building engineering. The efficiency, and thus the rate of a cutting process is mostly dependent on the type of a material being cut, the thickness of a material and on the parameters characteristic of a given process.

While selecting a cutting technology it is, first of all, necessary to take into consideration the following aspects [2]:
- grade and the thickness of a material being cut,
- length and the shape of a cutting line,
- required quality of edges cut (e.g. according to standards PN-EN 1090-2 [3] and PN-EN ISO

dr inż. Marek St. Węglowski (PhD Eng.) – Instytut Spawalnictwa, Testing of Materials Weldability and Welded Constructions Department, dr inż. Tomasz Pfeifer (PhD Eng.)– Instytut Spawalnictwa, Welding Technologies Department

9013 [4]) and the effect of a cutting process on the structure of a material,
- process potential and the effect on productivity,
- process-related costs such as a device purchase price, operating costs, spare parts costs, cutting-related costs (energy and materials).

While selecting the optimum cutting technology it is essential to carry out tests related to the quality of the cutting surface of elements made using various methods and techniques as well as carry out technical and economic analysis of the process. Heat sensitive materials additionally require microscopic metallographic examination aimed to determine the effect of a cutting process on the material structure following cutting. On the basis of test results the user can select a proper method and process technological conditions in order to meet normative requirements. A selected cutting process, treated as one of the stages of steel or aluminium structure production, needs to be properly controlled. This article presents an example-based effect of plasma cutting on the HAZ microstructure of elements subjected to cutting and specifies requirements concerned with cutting elements for welded structures, contained in PN-EN 1090-2 PN-EN ISO 9013 standards.

Microstructure and the properties of the HAZ of plasma-cut elements

The quality of plasma cutting is, in addition to surface geometrical features, manifested by the width and properties of HAZ. According to reference publications available, thermal cutting of unalloyed and higher strength alloy (low-alloy) steels leads to significant changes of HAZ material. In the cutting area it is possible to observe the changes of the chemical composition of a material near the cutting surface, an increase in hardness and brittleness as well as to the saturation of a material cut with gases (particularly nitrogen in cutting with air used as plasma gas [5-7]).

The changes of chemical composition can usually be observed in the case of higher strength alloy (low alloy) steels. The analysis of the HAZ chemical composition carried out using an electron microprobe revealed first, an increased carbon and nitrogen contents and second, significantly lower amounts of manganese and silicon in this area [5,6]. Microhardness measurements carried in the Heat Affected Zone also revealed significant hardening of subsurface areas [7]. In the case of cutting S355 steel with plasma, areas located 20 μm away from the cutting surface have a hardness of 850 μHV. The hardness of HAZ areas located further from the cutting surface decreases gradually to finally reach the hardness of the base metal (Fig. 1).

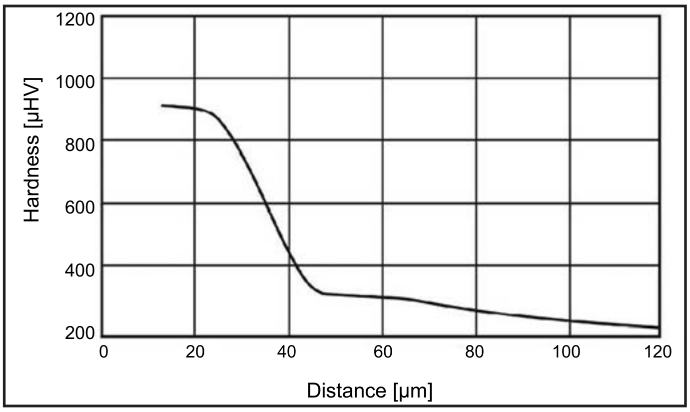

Fig. 1. Distribution of microhardness in the direction perpendicular to the cutting surface during plasma cutting of S355 steel [7]

A significant hardness increase in the area located very near the cutting surface is ascribed to strong nitrogenation during cutting with air used as plasma gas, which was confirmed by microscopic observations, microanalysis and X-ray tests revealing the existence of ε (Fe_2N) and γ' (Fe_4N) phases in subsurface layers [8, 9]. The increased hardness of a surface subjected to cutting can generate microcracks or operating cracks and poses a considerable problem during machining of elements cut out.

Due to the fact that plasma cutting is often one of the stages in the production of structures made of S690QL steel, it is of utmost importance to determine the effect of cutting process conditions on the properties of a material in the HAZ as the structure of the heat affected zone of plasma cut elements can significantly affect the operational properties of these elements. Stresses generated during thermal cutting may cause local exceedings of a yield point and lead to the generation of microcracks located on the cutting surface or in the heat affected zone. Such microcracks, affected by variable service loads may initiate the development of cracks and cause damage to elements. In order to prevent this, the hard, brittle and crack-susceptible HAZ microstructure (e.g. martensitic) should be removed after the completion of a cutting process. In turn, the removal of a zone with a microstructure similar to the base material structure is an unnecessary process and may increase manufacturing costs. If it becomes necessary to remove a zone of an unwanted microstructure, it is necessary to know its width, as it is also necessary to make appropriate allowances for machining. Making machining-related allowances significantly exceeding the HAZ width also increases manufacturing costs. Taking into consideration the foregoing, it appeared necessary to carry out the precise microscopic metallographic examination of the HAZ of elements cut out of 20 mm thick S690QL steel. The purpose of the examination was to determine the material structure and to measure the HAZ width [8,9].

The results of the metallographic examination revealed a relatively complex HAZ structure. On the cutting surface it was possible to observe a metal layer difficult to etch and having features of an amorphous material (Fig. 2 and 3). It was probably a metal which melted quickly during cutting and next underwent fast crystallisation. The width of the zone depends primarily on the cutting environment and, to some extent, on the cutting rate. The width tends to be smaller when the cutting rate is greater or during cutting under water. This probably results from the fact that during cutting under a water surface heat take-off from the cutting zone is faster. Because of this a smaller amount of material undergoes melting followed by crystallisation. The hardness in this zone amounts approximately to 400-450 HV. Outside this zone there is another one with a bainitic structure and constituting the core of the HAZ. The hardness of this zone is approximately 350-400 HV. It is easily seen that in the case of cutting in the air, the grain size is significantly bigger than during cutting under a water surface. Further from the cutting surface it is possible to observe a tempered martensite structure with a hardness of approximately 270-290 HV.

Fig. 2. Microstructure of the HAZ of the test element cut out of 20 mm thick S690QL steel using plasma; cutting in the air, a cutting rate of 0.50 m/min., mag. 200x [9]

Fig. 3. Microstructure of the HAZ of the test element cut out of 20 mm thick S690QL steel using plasma; cutting in the air, a cutting rate of 0.50 m/min., mag. 200x [9]

The metallographic examination also enabled carrying out HAZ width measurements. The tests revealed that the HAZ was primarily affected by the cutting rate and the environment in which a process was carried out. This dependence is connected with a heat input to the material. The lower the cutting rate, the greater the heat input, and consequently, the greater the HAZ width. Cutting under a water surface causes very fast and intense heat exchange with the environment, hence the HAZ width may be even two times narrower if compared with that obtained during cutting in the air using the same technological parameters. It should also be noted that the HAZ is rather slight and does not exceed 2 mm [9].

Presented below are requirements related to cutting elements intended for welded structures contained in PN-EN 1090-2 and referring to the production of welded structures for civil engineering purposes and general requirements related to cutting quality contained in PN-EN ISO 9013. On the basis of the test results discussed above it is possible to conclude that the requirements contained in PN-EN 1090-2 concerned with hardness measurements are not groundless as an increased hardness value may indicate that a structural transformation has taken place and a brittle crack-susceptible microstructure has been formed.

Requirements related to the surface quality after cutting according to PN EN 1090-2+A1:2012

Following the provisions contained in the standard, recognised cutting methods include cutting with a saw, cutting with a guillotine shear or a rotary cutter, cutting with a water jet and thermal cutting. Manual thermal cutting is used when mechanical thermal cutting proves impractical. PN EN 1090-2+A1:2012 specifies requirements concerned with a process of making steel structures or individual structural elements. According to the standard contents, cutting is carried out in a manner compatible with the requirements of standards and regulations in the scope of the following:

- geometric tolerances,
- maximum hardness,
- surface quality (smoothness).

Following the instructions of the standard, an incompatible process, i.e. failing to ensure required quality and accuracy, should not be used until corrected and verified again. Such a process can be used to a limited extent in the production of structural elements demonstrating compatibility features.

Particular attention should be paid to technologies used for cutting coated materials, e.g. materials provided with a passive layer, paint coating or electrolytic coating. While developing a cutting method for such materials it is necessary to try and minimise damage to coatings. First of all, it is necessary to remove burrs which may hurt humans or damage the surface of elements. In the case of corrosion-resistant steels the use of an improper technology will have to be followed by etching and passivation or repainting of damaged elements.

In the case of mechanical cutting cuts should be checked and, where necessary, smoothed in order to remove major defects. If cutting must be followed by grinding or machining, the processes should be carried out at least to the depth of 0.15 mm.

The usability of thermal (oxygen, plasma and laser) cutting should be verified periodically. The frequency of inspections should depend on the size of production, frequency of technology modifications or the kind of elements being cut. A structural element is sampled for four test pieces which are next subjected to the following processes:

- straight cutting of the thickest part,
- straight cutting of the thinnest part,
- cutting out a sharp corner in the part having a representative thickness,
- circular path cutting in the part having a representative thickness.

Figure 4 presents an exemplary test element.

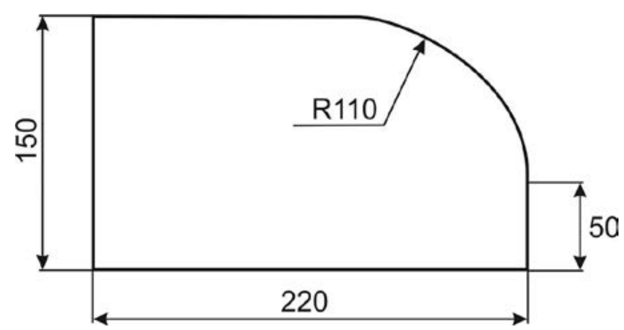

Fig. 4. Test element for surface quality inspection after cutting

A required quality class should be verified on flat test pieces of a length not shorter than 200 mm. Test pieces for cutting out sharp corners and for circular path cutting should be checked for the quality of edges in accordance with standards concerned with straight cutting. The standard PN-EN 1090-2 related to inspecting the quality of cut surfaces cites the standard PN-EN ISO 9013. The surface quality after cutting should meet the following requirements:

- in the case of EXC1 class edges free from significant irregularities after cutting are acceptable provided all impurities have been removed using slag. In such case it is possible to use u tolerances in range 5 in relation to perpendicularity or inclination;
- Table 1 contains requirements concerning other workmanship classes.

Table 1. Surface quality after cutting

	Tolerance of perpendicularity or inclination, *u*	**Average shape height, *Rz5***
EXC2	Range 4	Range 4
EXC3	Range 4	Range 4
EXC4	Range 3	Range 3

If the ordering party requires carrying out hardness measurements, the maximum surface hardness of elements made of unalloyed steel after cutting should not exceed the values presented in Table 2. In cases when cutting processes may lead to local hardening (thermal cutting, cutting-off, cutting out) these processes should be checked for their usability prior to practical implementation. In order to meet the requirements related to the hardness of surface after cutting it is possible to make use of pre-heating.

Table 2. Allowed maximum hardness (HV10)

Product standards	**Steel grade**	**Maximum hardness**
EN 10025-2 to -5	S235 to S460	380
EN 10210-1, EN 10219-1		
EN 10149-2 and EN 10149-3	S260 to S700	450
EN 10025-6	S460 to S690	

Note: According to EN ISO 15614-1 [11] values apply to steel grades listed in ISO/TR 20172 [12]

If the ordering party has not specified special quality control conditions, process usability is carried out in the following manner:

- structural element most susceptible to local hardening is sampled to obtain four test pieces for procedural tests;
- each test piece is subjected to four hardness tests according to PN-EN ISO 6507 [3] in the places most susceptible to hardening.

Requirements related to the surface quality after cutting according to PN-EN ISO 9013:2008

In accordance with the instructions contained in the standard, surface quality assessment after cutting can be carried out by means of precise or rough measurement instruments. While selecting a measurement instrument it is necessary to bear in mind that the boundary values of a measurement error must not exceed 20% of the characteristic parameters to be measured. Measurements should be carried out on cutting surfaces cleaned with a brush, free from oxides, outside areas containing imperfections. The upper and lower side of a thermally cut object constitute reference elements. Surfaces should be even and clean.

In order to identify rectilinearity a reference element and a straight measurement line should be positioned in relation to each other so that the maximum distance between straight measurement lines and a real surface is minimum. The minimum condition is explained in detail in PN-EN ISO 1101:2013 [14].

The location of measurement points and their number depend on the shape and size of an object subjected to machining and on an intended application. The standard PN-EN ISO 9013 provides general instructions:

- while selecting measurement points it is necessary to remember that the maximum

values of the average profile height and of the tolerances of perpendicularity and inclination can be located in different points on the cutting surface,
- measurement points should be located in places where the maximum values of individual characteristic parameters are predicted,
- due to measured maximum values, surfaces after cutting are classified by the standard as being in tolerance fields,
- if measured values are near the lower or upper tolerance field limits, in disputable situations it is necessary to carry out supplementary tests,
- number and location of measurement points should be specified by the manufacturer. If no specific requirements were provided, it is necessary to carry out
  - two times three measurements of the u value 20 mm one from the other on each meter of cutting,
  - one measurement of the *Rz5* value on each meter of cutting.
- characteristic value of the tolerance of perpendicularity or inclination *u* will be determined only in a limited cutting surface area. The area should be limited by the dimension *Δa*, in accordance with Table 3, and subtracted from the upper and lower edges of the cutting surface (Fig. 5). The reasons for limiting the shape of the butting surface of cutting are the deformations of the upper and lower edges, resulting from the specific character of individual processes.
- if the thickness of a sheet is less than 2 mm, a measurement procedure for determining the tolerance of perpendicularity or inclination should be previously agreed.
- characteristic value of the average shape height *Rz5* will be determined only in a limited cutting surface area. A measurement is carried out in the point having the maximum porosity on the cutting thickness in accordance with PN-EN ISO 4288:2011E [15].
- in the case of oxygen cutting and plasma cutting a measurement usually takes place at a distance amounting to ⅔ of the cutting thickness from the upper cutting edge; in the case of laser cutting at a distance amounting to ⅓ of the cutting thickness from the upper cutting edge. For a cutting thickness below 2 mm a measurement is carried out at a distance amounting to ½ of the cutting thickness from the upper cutting edge.
- characteristic values for the cutting surface will be determined in accordance with the type of measurement using appropriate instruments.
- average shape height *Rz5* should be measured 15 mm away from the start of cutting in the advancing direction. A measurement is carried out in accordance with PN-EN ISO 4288:2011E using a device described in PN-EN ISO 3274:2011E [16].

Table 3. Dimensions Δa depending on the thickness of a sheet

Thickness of sheet cut, *a* [mm]	**Δa [mm]**
≤ 3	0,1 a
> 3 ≤ 6	0,3
> 6 ≤ 10	0,6
> 10 ≤ 20	1,0
> 20 ≤ 40	1,5
> 40 ≤ 100	2,0
> 100 ≤ 150	3,0
> 150 ≤ 200	5,0
> 200 ≤ 250	8,0
> 250 ≤ 300	10,0

In accordance with the provisions of the standard PN EN ISO 9013 the quality of material surface after thermal cutting is described by means of the following characteristic parameters:
- tolerance of perpendicularity or inclination, *u*,
- average shape height, *Rz5*.

It is also possible to use additional parameters:
- cutting line deflection, *n*,
- partial melting of the upper edge, *r*,
- possible presence of slag or a metal drop adhering to the lower cutting edge.

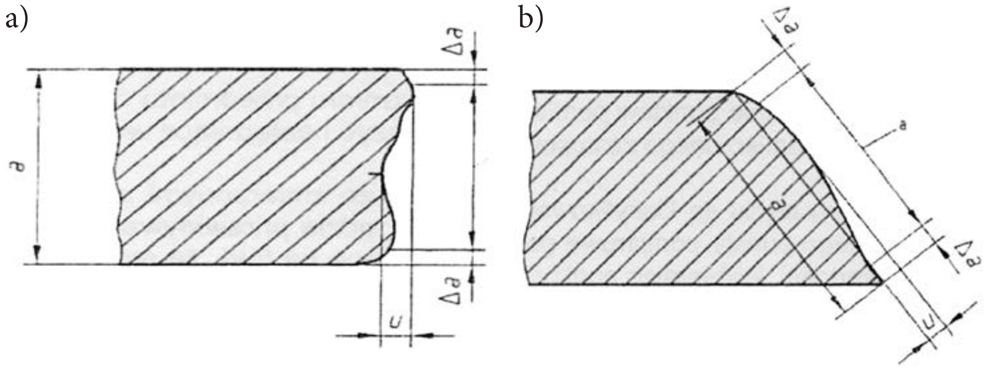

Fig. 5. Determining a measurement range for the tolerance of perpendicularity and inclination; a) perpendicular cut, b) bevel cut

It should be remembered that not every quality tolerance and not every product geometry deviation can be achieved by every process and for every material. For instance, the cutting surfaces of elements made of aluminium, titanium, magnesium and their alloys as well as of elements made of brass, if the microstructure of an alloy is coarse-grained, have corrugations on which it is not possible to determine the average shape height and obtain an assessment in accordance with the standard PN-EN ISO 9013. For aluminium and its alloys such values can be on the average four times higher than those specified in the requirements of this standard. In the case of oxygen and plasma cutting, the tolerance of perpendicularity and inclination does not apply to the start and the end of cutting or to small radiuses and acute angles.

In the case of elements having many cutting surfaces such as Y-shaped or double V-shaped joints each cutting surface should be evaluated separately. The value of the tolerance of perpendicularity or inclination, u, is presented in Table 4. The allowed ranges of the average shape height, *Rz5*, are presented in Table 5.

Table 4. Tolerance of perpendicularity or inclination, *u*

Range according to PN EN ISO 9013	Tolerance of perpendicularity or inclination, *u*, mm
1	0.05 + 0.003a
2	0.15 + 0.007a
3	0.4 + 0.01a
4	0.8 + 0.02a
5	1.2 + 0.035a

Table 5. Average shape height, Rz5

Range according to PN EN ISO 9013	Average shape height, Rz5, μm
1	10 + (0.6a mm)
2	40 + (0.8a mm)
3	70 + (1.2a mm)
4	110 + (1.8a mm)

The standard PN EN ISO 9013 does not contain specified quality levels or tolerance classes for such defects as grooving, inevitable formation of drops or slag on the lower cutting edge or a characteristic threshold formed during the commencement of a cutting process or oxidised layer residues on the cutting surface. Such defects are usually assessed following the customer's requirements who should specify acceptance criteria.

Testing methodology

The tests of the effect of a technology on surface quality after cutting were carried out on a 10 mm thick S355J2+N steel sheet. The tests included cutting out test elements (Fig. 4) for various cutting process conditions (Table 6) and carrying out a quality assessment based on the requirements of PN-EN 1090-2 PN-EN ISO 9013. The process technological conditions were selected after taking into consideration the kind and thickness of a material.

The quality control tests included the measurements of the shape height *Rz5*, perpendicularity tolerance and surface hardness after cutting. The measurements of the shape height *Rz5* were carried out in accordance with the standard PN-EN ISO 4288:2011 using a Mitutoyo-manufactured SJ210 contact profile measurement gauge; the number of roughness sampling cut-offs amounted to 5, the travel rate was 0.5 mm/s, and the total shift amounted to 17.5 mm.

Table 6. Cutting process technological conditions

Test piece no.	Cutting technology	Device	Cutting rate, m/min	Remarks
1	oxygen (propane)	Messer Alfa	0.42	oxygen pressure during heating 2.0 bar, cutting pressure 4.5 bar,
2	high definition plasma (HD)	HD3070 by Hypertherm	0.7	oxygen as cutting gas
3	laser beam	Trumatic 2600 (Trumpf)	1.2	
4	plasma over a water surface	CP200 (Instytut Spawalnictwa)	1.6	
5	plasma over a water surface		2.25	
6	plasma under a water surface		1.6	
7	water jet	WaterJet NC3015	0.13	Australian sand used as powder
8			0.16	
9			0.18	

Hardness measurements were carried out using Brickers 220 Krautkramer MIC 20 hardness testers. The measurements were carried out using the Vickers method under a load of 98.1 N (HV 10) and the Leeb method using a metal ball on the cutting surface after removing a tarnish layer and on a metallographic specimen sampled perpendicularly to the cutting surface.

In the Leeb method, during a measurement a beater with a tip made of sintered carbides is thrown with a spring force towards a measured surface against which it springs back. The impact and rebound velocity is measured in the following manner: a permanent magnet placed in the beater passes through a coil and excites voltage while passing to and fro. This voltage is proportional to the velocity. Values measured are processed in a device and converted to a hardness value L.

The measurements of perpendicularity tolerance were made using a dial gauge with an accuracy of 0.01 mm. A test plate moved in relation to the gauge with a rate of 15 mm/min.

The research work also involved microscopic metallographic tests, the purpose of which was to assess the steel microstructure after cutting and to the HAZ width. To this end, the metallographic specimens after grinding and polishing were etched with the Nital reagent. Observations were carried out using a Nikon-made Eclipse MA 200 metallographic microscope.

Test results and discussion

Table 7 presents the results of perpendicularity tolerance measurements carried out on a test element in the places presented in Figure 6. The analysis of the data presented in the table reveals that the lowest perpendicularity tolerance (the highest cutting quality) was obtained for laser beam cutting and HD plasma cutting, whereas the highest (the worst quality) for cutting over a

Table 7. Results of perpendicularity tolerance measurements in the points presented in Figure 6.

Test piece no.	Place of measurement			
	1	2	3	4
	Perpendicularity tolerance [mm]			
1	0.20	0.20	0.30	0.30
2	0.12	0.08	0.18	0.24
3	0.17	0.10	0.06	0.15
4	1.70	1.60	1.15	1.08
5	1.30	1.20	0.85	0.85
6	1.60	1.20	1.05	0.8
7	0.35	0.30	0.30	0.30
8	0.38	0.50	0.35	0.35
9	0.50	0.40	0.30	0.40

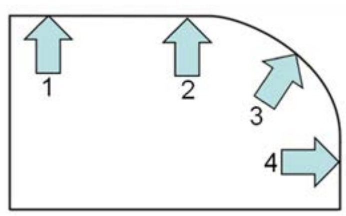

Fig. 6. Location of the measurement points on the test element

water surface at a cutting rate of 1.6 m/min. Significant energy density in HD plasma cutting and laser cutting causes the jet to be more concentrated (i.e. having a smaller diameter), which ensures better surface quality after cutting. It should be noted that in the case of HD plasma cutting and laser cutting the rate of cutting is high (0.7 and 1.2 m/min respectively) in comparison with oxygen or water jet cutting, yet lower than the rate of plasma cutting (1.6 and 2.25 m/min).

The assessment of the cutting technology effect on the HAZ hardness required carrying out Leeb hardness tests on a metallographic specimen sampled perpendicularly to the surface after cutting (Fig. 7) and on the surface after cutting (Fig. 6). The results of measurements are presented in Tables 8 and 9. The hardness measurement result analysis reveals the highest hardness results for test piece no. 6 (plasma cutting under a water surface). Fast heat take-off is responsible for a short cooling time $t_{8/5}$, and, as a result, in the case of S355 steel leads to the formation of martensitic-bainitic microstructures (Fig. 8) characterised by higher hardness. A water shield, affecting the thermal conditions of a material being cut, causes the HAZ decrease and the deformation of elements being cut, yet at the same time it may reduce the cutting rate and consequently efficiency. The basic advantage of cutting under a water surface is the improvement of work conditions on the workstation and the elimination of the detrimental effect of the plasma arc. The use of water reduces the emission of fume, ozone and noise (significantly) [17]. The lowest hardness was achieved for the test pieces cut with a water jet. In this case there is no heat source, the process of cutting is connected with abrasive micro-machining, the microstructure does not change (Fig. 9) and the hardness corresponds to that of the base metal (about 140 HV).

The research-related tests also involved examining the effect of a cutting technology in the HAZ width. On the basis of the measurements conducted it is possible to state that the widest HAZ was obtained with oxygen cutting (Fig. 10), whereas the narrowest (the lack of HAZ) was obtained in the case of the surface cut with a water jet (Fig. 9). The cumulative results are presented in Figure 11.

Table 8. Results of HV10 hardness measurements on the metallographic specimen sampled in the place presented in Figure 7.

Test piece no.	Place of measurement				
	1	2	3	4	5
	Hardness HV10				
1	294	218	162	164	161
2	341	207	154	152	145
3	256	169	150	156	161
4	368	261	169	158	151
5	337	177	160	147	145
6	374	307	177	156	151
7	126	141	141	139	143
8	127	140	140	141	137
9	137	143	145	142	143

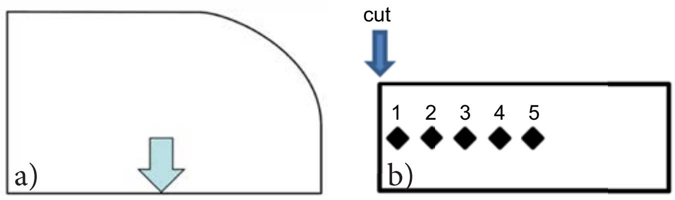

Fig. 7. Test element with the marked place of hardness measurements, a) metallographic specimen sampling place, b) location of measurement points

Table 9. Results of hardness measurements using an indirect method and converted to the Vickers scale

Test piece no.	Place of measurement			
	1	2	3	4
	Hardness HV10 converted			
1	270	296	273	285
2	247	272	263	252
3	234	220	269	230
4	343	343	327	343
5	301	321	291	293
6	349	347	371	367
7	150	157	154	145
8	145	157	144	140
9	146	144	141	141

Note: the values in the table have been averaged on the basis of 3 measurements

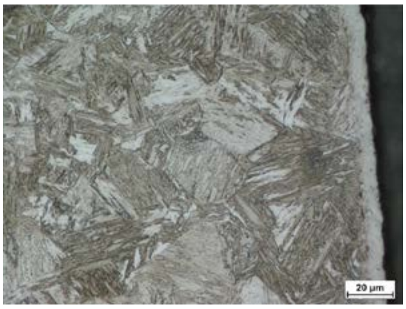

Fig. 8. Microstructure of the HAZ of the area cut with plasma under a water surface, v_c=1.6 m/min. Martensitic--bainitic microstructure, etching with Nital reagent

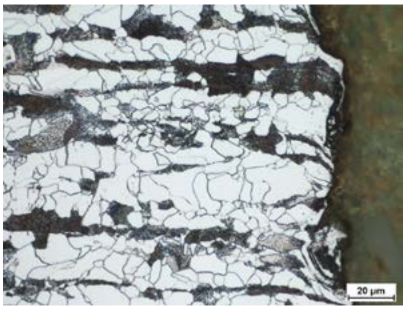

Fig. 9. Microstructure of the area after water jet cutting, v_c=0.16 m/min. Ferritic-pearlitic microstructure, etching with Nital reagent

Fig. 9. Microstructure of the area after water jet cutting, v_c=0.16 m/min. Ferritic-pearlitic microstructure, etching with Nital reagent

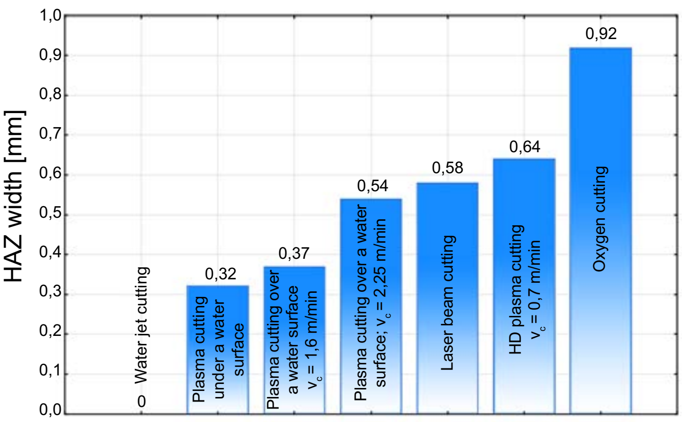

Fig. 11. Effect of a cutting technology on the HAZ width of a surface cut

An important parameter as regards the correctness of a cutting process is the shape height *Rz5* indicating the porosity of the cutting surface. The results of measurements are presented in Table 10. The measurements were carried out on the test element in 4 points (Fig. 4). The results revealed the highest porosity for the element cut with a laser beam, and the lowest for the element cut with plasma over a water surface at a cutting rate v_c=2.25 m/min.

The greater value of the shape height for the laser cutting surface results from the cyclicity of the cutting process itself. The process of cutting with a laser beam is connected with the multiple start and extinction of a combustion reaction in the upper part of a metal. The process of oxidation (the cutting process involved the use of oxygen as a cutting gas) leads to the formation of ducts in the material. For a lower cutting rate (in the test the cutting rate was 1.2 m/min) the ducts are “thicker” and less concentrated [18]. Laser beam cutting leaves deep marks on the surface.

Table 10. Results of Rz5 shape height measurements

Test piece no.	Place of measurement			
	1	2	3	4
	Rz5 [μm]			
1	20.84	15.32	22.11	27.10
2	15.54	10.61	10.49	19.69
3	34.29	30.24	30.54	52.37
4	17.93	17.38	14.02	12.55
5	13.23	14.32	8.10	9.86
6	18.64	13.84	10.25	8.55
7	24.19	22.54	25.41	25.80
8	23.68	25.07	28.10	21.81
9	21.60	25.89	33.44	26.55

Concluding remarks

On the basis of the tests conducted it is possible to formulate the following conclusions:

- requirements related to the quality of surfaces cut according to PN-EN ISO 1090 standard are of importance as regards the selection of a proper cutting process,
- properly selected process technological conditions ensure obtaining the required quality of cut surfaces,
- lowest surface hardness following cutting is ensured by water jet cutting, whereas the

highest is obtained using cutting under a water surface,
– lowest surface porosity is ensured by plasma cutting over a water surface and the highest by cutting with a laser beam,
– lowest perpendicularity is obtained by plasma cutting under a water surface 1.6 m/min, whereas the highest by laser beam cutting and plasma HD cutting.

References

1. Keitel S., Muller U., Strofer M., Muglitz J.: Przestrzenne cięcie termiczne – techniczne rozwiązania i przykłady zastosowania. Biuletyn Instytutu Spawalnictwa, 2001, vol. 45, No. 5, pp. 87-91.
2. Klimpel A.: Technologie spawania, zgrzewania i cięcia metali. WNT, Warszawa 2000.
3. PN-EN ISO 9013:2008 Thermal cutting - Classification of thermal cuts - Geometrical product specification and quality tolerances
4. PN-EN 1090-2+A1:2012P Execution of steel structures and aluminium structures. Part 2: Technical requirements for steel structures.
5. Tasak E.: Zmiany zachodzące w strefie wpływu ciepła podczas cięcia termicznego. Przegląd Spawalnictwa 1982, No. 2,3, pp. 17-20.
6. Brózda J.: Zmiany składu chemicznego i struktury zachodzące w stali w pobliżu powierzchni cięcia termicznego. Prace Instytutu Spawalnictwa, 1979, No. 1, 34-41.
7. Górka J.: Zmiany zachodzące w strefie wpływu ciepła podczas cięcia plazmą powietrzną. Materiały konferencyjne Sympozjum Katedr i Zakładów Spawalnictwa, Rudy 1997.
8. Pfeifer T.: Budowa strukturalna i własności SWC elementów wycinanych plazmowo ze stali o wysokiej wytrzymałości - Part I. Stal, 2013, No. 7-8, pp. 54-56.
9. Pfeifer T.: Budowa strukturalna i własności SWC elementów wycinanych plazmowo ze stali o wysokiej wytrzymałości - Part II. Stal, 2013, No. 9-10, pp. 92-96.
10. Ferenc K.: Cięcie strumieniem wody. Przegląd Spawalnictwa, 2006, No. 7, pp. 10-15.
11. PN EN ISO 15614-1:2008A2:2012E Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys
12. ISO/TR 20172 ISO/TR 20172:2009 Welding - Grouping systems for materials - European materials.
13. PN-EN 6507-1:2006 Metallic materials - Vickers hardness test - Part 1: Test method
14. PN EN ISO 1101:2013 Geometrical product specifications (GPS). Geometrical tolerancing. Tolerances of form, orientation, location and run-out
15. PN-EN ISO 4288:2011 Geometrical Product Specifications (GPS) - Surface Texture: Profile Method - Rules And Procedures For The Assessment Of Surface Texture
16. PN-EN ISO 3274:2011E Geometrical product specifications (GPS) - Surface texture: Profile method - Nominal characteristics of contact (stylus) instruments
17. Czech J., Dworak J.: Underwatter plasma cutting. Biuletyn Instytutu Spawalnictwa, 1996, vol. 40, No. 3, pp. 39-43.
18. Faerber C.: Cięcie laserowe – aktualny stan rozwoju technologii. Przegląd Spawalnictwa, 2007, No. 6, pp. 12-14.