ISSN 1330-3651
UDC/UDK 621.791.94:669.14.018.29

COMPARISON OF DIFFERENT MATERIAL CUTTING TECHNOLOGIES IN TERMS OF THEIR IMPACT ON THE CUTTING QUALITY OF STRUCTURAL STEEL

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Subject review

The paper deals with a comparison of the most frequently used thermal cutting technologies applied to the structural, low carbon steel EN S355J0 in engineering enterprises with a focus on experimental measurement and evaluation of characteristics of the heat affected zone. It gives a mutual comparison of these technologies in terms of the achieved heat affected zone. The goal of this paper was to use the property changes in the used material (affected by laser, plasma arc and oxygen cutting) as the quality indicator of the cutting process.

Keywords: *heat affected zone, metallography, structural steel, quality, thermal cutting*

Usporedba utjecaja različitih tehnologija rezanja materijala na kvalitetu reza konstrukcijskih čelika

Pregledni članak

U radu se daje usporedba najčešće korištenih toplinskih postupaka rezanja, koje koriste proizvodne tvrtke, u primijeni na konstrukcijskom, nisko ugljičnom čeliku EN S355J0 s naglaskom na eksperimentalna mjerenja i vrednovanje svojstava zone utjecaja topline. Rad prikazuje usporedbu tih tehnologija u kontekstu dobivene zone utjecaja topline. Cilj ovog rada je korištenje spoznaje o promjenama svojstava korištenog materijala na površini reza (dobivene laserom, plazmom i plinskim rezanjem) kao pokazatelja kvalitete procesa rezanja.

Ključne riječi: *konstrukcijski čelik, kvaliteta, metalografija, toplinsko rezanje, zona utjecaja topline*

1
Introduction
Uvod

Developments in the field of the material cutting technologies are stimulated by engineering requirements for production, and include: improvements in productivity, high operational reliability, universality, enhancing of quality parameters, and last but not least, environmental criteria. In addition to the conventional material cutting technologies, the advanced cutting technologies with a high power density, such as plasma arc, laser beam, and so on have been generated in recent years. Due to different energy sources many experiments related to their suitability of usage were carried out. Therefore it is desirable to recall that the advanced cutting technologies do not compete with traditional technologies but help to expand opportunities for engineers and technologists. Neither cutting technology is universal; each has a limited field of application. To choose an appropriate technology it is needed to know the familiar patterns of technologies in relation to science – engineering – production. Each production company has a desire to improve its productivity. These improvements may also require considerable investments. The competitiveness of engineering enterprises today depends mainly on quality improving and price undercutting of products.

2
Problem definition
Definiranje problema

The issue of comparing the different technologies is extensive and not always clearly limited [1, 2, 3, 4]. When choosing a cutting technology there is a need to consider not only economic but also technical and technological parameters [5, 6, 7, 8, 9]. The goal of this experiment was to evaluate the quality of the divided surface areas in terms of the heat effect and also to provide an overview of the use of technologies [10] for a given type of steel in practice. The measurements of micro hardness within the heat affected zone provide an important piece of information and vision about the thermal influence on a basic material. A common denominator is to achieve a good cutting quality. The quality criteria of thermal cuts describe as the best the German standard DIN 2310-6, although mainly in the automotive industry the appearance, accuracy and the cut surface quality are often evaluated according to ASTM specifications (American Society For Testing Materials). The general quality criteria include: surface roughness, geometry of the cut, occurrence of dross and heat affected zone. To select an appropriate method for metal cutting is influenced by a number of factors that significantly affect compliance of the obtained results. Nowadays are still in practice preferred as conventional and unconventional technologies of material cutting. The thermal cutting processes are classified into different categories according to DIN 2310. The classification of thermal cutting includes: physics of the cutting process, degree of mechanization, type of energy source and arrangement of the water bath. It also describes the principle of oxygen cutting, plasma arc cutting and laser beam cutting [11]. The principle of the metal cutting technology by oxy-acetylene flame is a combustion process of iron burning that is heated to the ignition temperature in a stream of oxygen. A divided material burns (combines) with oxygen to form oxides, which are in the form of a liquid slag due to dynamic effect of oxygen blown away from the cutting gap. The combustion process, which produces different types of iron oxides is a strongly exothermic reaction, i.e., with a large evolution of heat (autogenously) at the place of cutting. A metal that we want to cut, must fulfill the following requirements for divisibility:

- heat released during combustion must be sufficient in order to maintain the ignition temperature of the material at the place of cutting,
- ignition temperature must be lower or the same, as the melting temperature of the material being cut,

- melting temperature of the produced oxides must be lower or the same as the melting temperature of the material being cut so that oxides could be continuously blown away by the oxygen jet [12].

The principle of plasma arc cutting consists in melting of material by extreme temperatures, developed by molecular decomposition of gas when passing through electric arc. The arc burns between a non fusing tungsten electrode and anode that consists of the working material and the torch body. The properties of the process are characterized by the current power source, design of nozzles, and the type of the process (single-gas, double- gas, water injection or underwater) as well as the type of plasma and focusing gas. Depending on the type of plasma this method is appropriate for cutting carbon, high-alloy steels, aluminum, copper and so on [11]. The technology of laser cutting is a process in which the material is heated to a melting temperature or sublimation, and this is achieved by concentrating the laser beam energy to a very small area [13]. Metals, ceramics, polymers and natural materials as wood, rubber, can be cut by laser [14, 15, [16]. For steel cutting, oxygen as the additional gas plays an important role providing the exothermic energy for the process. On the basis of that, greater thickness – up to 20 mm can be cut and the cutting quality and speed are considered to correspond to those of other thermal cutting processes. The laser cutting is considered to be as low destructive as the other heat options [17]. Among the basic parameters defining the process belong: thickness of the material being cut, laser power, cutting speed, gas purity, pressure and flow of auxiliary cutting gas [18]. The laser cutting efficiency is determined by physical mechanisms such as conductivity, phase change, plasma formation and surface absorption [19]. A development in laser cutting leads not only to the increase of the laser power but it also helps improve a software solution.

3
Eksperimental set up
Plan eksperimenta

To compare the above mentioned material cutting technologies in terms of the achieved properties of structural steel, the material of EN S355J0 was used. It is a non–alloyed fine-grain structural steel with a guaranteed cold weldability. It is suitable for welded structures with higher strength, for machinery parts, and transport equipments, for the production of low-stress rotating parts. The chemical composition of the used material is given in Tab. 1.

***Table 1** Chemical composition of the used material EN S355J0*
***Tablica 1.** Sadržaj kemijskih elementa u ispitnom materijalu EN S355J0*

C	Mn	Si	P	S	N
max. 0,20	max. 1,60	max. 0,55	max. 0,04	max. 0,04	max. 0,009

3.1
Experimental test procedure
Postupak mjerenja

To compare the above mentioned material cutting technologies in terms of the achieved properties of the structural steel EN S355J0 the samples of 150 × 150 mm size were cut in three different thicknesses of 10 mm, 15 mm, and 20 mm. The cutting process was carried out at optimal machine settings, i.e. the settings proposed by a control system after entering the parameters of the cut material. When cutting these samples by oxygen (by cutting machine Multitherm 3100 from the Messer Cutting System corporation), by plasma arc (plasma cutting machine Advanced HD 3070) and by laser (laser cutting machine Platino 2040/ CP 3500), the parameter settings of each machine were recorded. The measurement of microhardness and qualitative and quantitative evaluation of the heat affected zone (HAZ) followed after cutting all of these samples. The cutting parameters obtained by oxygen cutting are listed in Tab. 2, by plasma cutting in Tab. 3 and by laser cutting in Tab. 4.

***Table 2** Cutting parameters by oxygen cutting*
***Tablica 2.** Parametri plinskog rezanja*

Cutting thickness/mm	10	15	20
Cutting speed/ mm/min	561	503	417
Nozzle diameter/ mm	1,2	1,4	1,4
Oxygen pressure/ bar	5 ÷7	6÷7	6÷7

***Table 3** Cutting parameters by plasma cutting*
***Tablica 3.** Parametri rezanja plazmom*

Cutting thickness/ mm	10	15	20
Cutting speed/ mm/min	2300	1200	1000
Arc voltage/ V	142	144	144
Cutting height/mm	3	4	4
Punch gap/ mm	5	8	8
Amper (cutting speed)	100	200	200
Amper (deceleration)	100	200	200
Z – axis speed (0 – 100)	15	15	15

***Table 4** Cutting parameters by laser cutting*
***Tablica 4.** Parametri rezanja laserom*

Cutting thickness/ mm	10	15	20
Lens type	7,5"	7,5"	7,5"
Laser power/ W	3300	3500	3500
Nozzle diameter/ mm	2	2	2
Type of the regime	99 % CW	99 %	99 %
Frequency/ Hz	2000	2000	2000
Oxygen purity	3,5	3,5	3,5
Gas pressure/ bar	0,2	0,3	0,45
Nozzle settings/ mm	1,2	1,2	1,2
Focus/ mm	1	1,5	2,5
Cutting speed/ mm/min	1500	1100	760

3.2
Microhardness measurement of the heat affected zone
Mjerenje mikrotvdoće u zoni utjecaja topline

The microhardness measurements of the heat affected zone on the base of material matrix were carried out by the automatic micro hardness tester AMH43. This device works on the principle of impressing a diamond in the form of a square – based pyramid into the tested surface of material with a load F. The size of the load was 100 grams and the loading period was 10 s. The microhardness measurements were performed 1 to 2 mm equally distant from the edge cut with 0,1 mm step of measurement (Fig.1). To examine the metal structure after the thermal cutting a metallurgical microscope Olympus GX-41 was used.

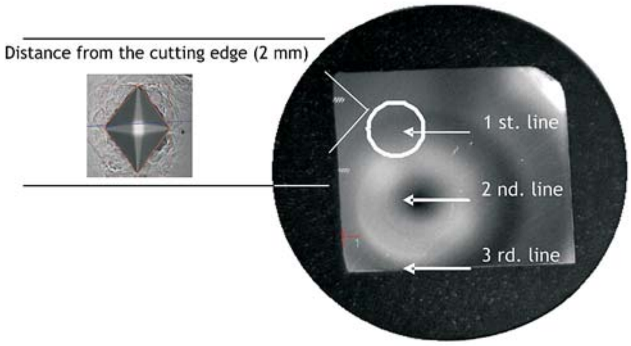

Figure 1 *Principle of the microhardness measurement*
Slika 1. *Princip mjerenja mikrotvrdoće*

4
Results and discussion
Rezultati i rasprava

The microhardness measured at a distance of 2 mm from the edge of the cut was used as the determining criterion. The measurements were performed within the three lines of the samples, i.e. in a distance of 2 mm from the cutting edge and in the middle of the sample. The measurements of microhardness after the oxygen cutting according to Vickers showed that the resulting heat affected zone was wider as compared to plasma and laser, depending on the material thickness. In all three cases (using three different thicknesses) the microhardness increased. The largest increase of the microhardness occurred at a thickness of 15 mm i.e. by an average of 90 HV1, then at a thickness of 20 mm by an average of 70 HV1 and the minimum increase was at a thickness of 10 mm where it was by an average of 60 HV1 (Fig. 2, 3, 4).

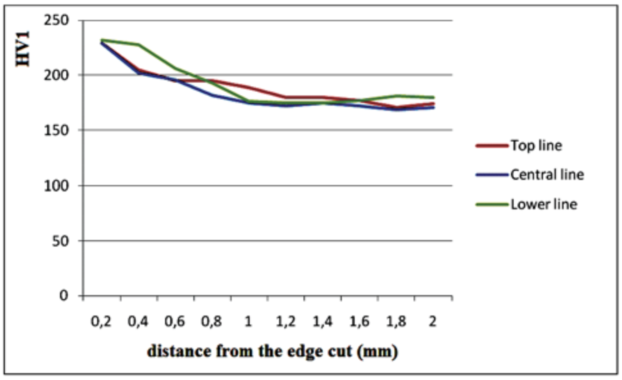

Figure 2 *Microhardness measurements after the oxygen cutting at a thickness of 10 mm*
Slika 2. *Rezultati mjerenja tvrdoće nakon plinskog rezanja pri debljini 10 mm*

Due to the high rate of heating with no holding at the maximum temperature there is usually only a partial transformation. The phase transition $\alpha \rightarrow \gamma$, carbide dissolution and especially homogenization of the austenite depends not only on the temperature, but also on the rate of heating as well as on the time of holding at the maximum temperature. An austenite grain that grows when heating rapidly is much softer and with an increased temperature it thickens more slowly because the higher the heating rate, the later the grain thickens.

The lack of heating (the low temperature of austenitizing for a given heating rate when oxygen cutting) results in a weak degree of homogenization of the austenite, resulting in an increase of the critical cooling rate with the occurrence of troostite and when incomplete phase transformation the ferrite remains are also presented in the resulting structure.

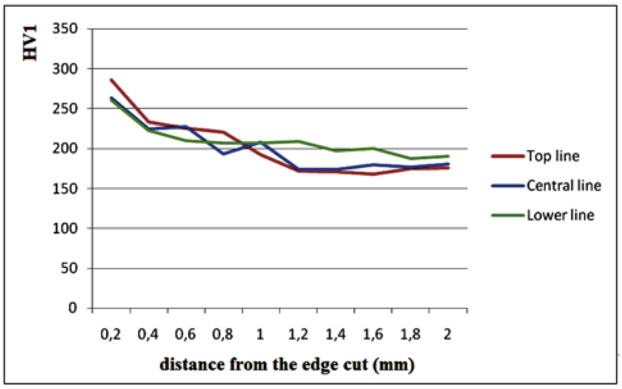

Figure 3 *Microhardness measurements after the oxygen cutting at a thickness of 15 mm*
Slika 3. *Rezultati mjerenja tvrdoće nakon plinskog rezanja pri debljini 15 mm*

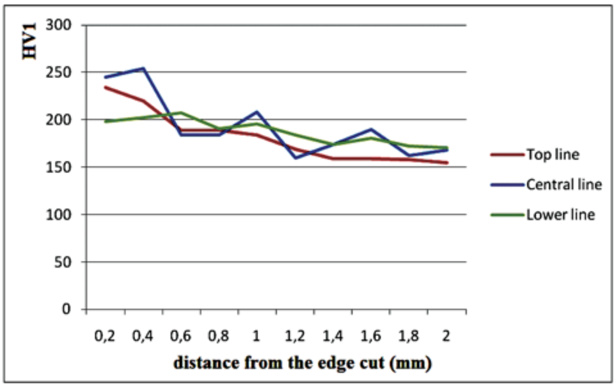

Figure 4 *Microhardness measurements after the oxygen cutting at a thickness of 20 mm*
Slika 4. *Rezultati mjerenja tvrdoće nakon plinskog rezanja pri debljini 20 mm*

When oxygen cutting, structural steel practically does not temper and the thermal effect on its structure is said to be insignificant. Around the cutting surfaces there is a change of the grain size (the high heating zone) which may cause the occurrence of not only perlite but also of equilibrium component of sorbitol. The sorbitol bodies are not sufficiently developed, because the heating time over the temperature A_{c3} (the zone of normalization) is very short, so the metal structure remains inhomogeneous. In addition, the metal heats very quickly when cutting, so that the interval of changes between $A_{c1} - A_{c3}$ moves to the higher temperatures and in a wide range of the thermal effect there is only partial, incomplete recrystallization, where the grain size softening has been observed (Fig. 5).

A sorbitic structure within the heat affected zone does not cause reduction of the steel quality but improves its mechanical properties, in particular the strength without a significant reduction in ductility and notch toughness. The changes of the steel structure depend on the thickness of material and also on the chemical composition of the material. The thicker the steel sample is, the greater the heat effect and also the layer thickness of metal (in which the changes in structure take place) is [120], [21]. For example the changes in microhardness, which were considered as the determining criterion, took place at thickness of 20 mm into a depth of 2 mm from the cutting edge, at thickness of 15 mm they took place into a depth of 1,4 mm from the cutting

Figure 5 *The HAZ transition after the oxygen cutting – magnification* 100×
Slika 5. *Prijelaz ZUT-a nakon plinskog rezanja – povećanje* 100×

edge and at thickness of 10 mm they took place into a depth of 1 mm from the cutting edge.

When evaluating the HAZ after the plasma arc cutting, the same criteria as in previous methods have been followed. The microhardness measurements showed much higher values on the scale of HV1, compared to laser and oxygen. The highest increase occurred at the thickness of 20 mm by an average of 255 HV1, whereas the changes in microhardness took place into a depth of 0,7 mm from the cutting edge. When reducing the thickness of the material, the values of microhardness have varied at the thickness of 15 mm by an average of 245 HV1 whereas the change took place into a depth of 0,5 mm from the cutting edge. The smallest increase occurred at the thickness of 10 mm by an average of 115 HV1 where it took place into a depth of 0,4 mm from the cutting edge Fig. 6, 7, 8.

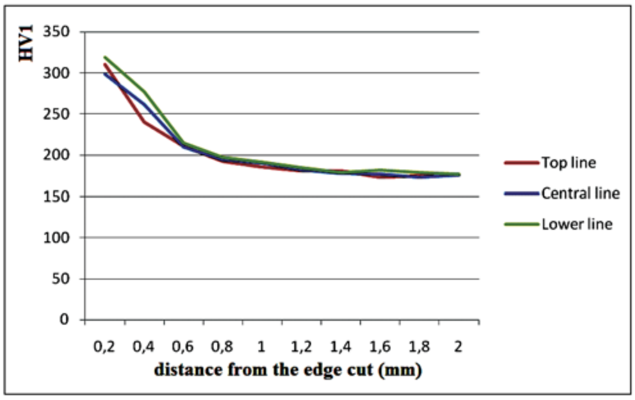

Figure 6 *Microhardness measurements after the plasma cutting at a thickness of 10 mm*
Slika 6. *Rezultati mjerenja tvrdoće nakon rezanja plazmom pri debljini 10 mm*

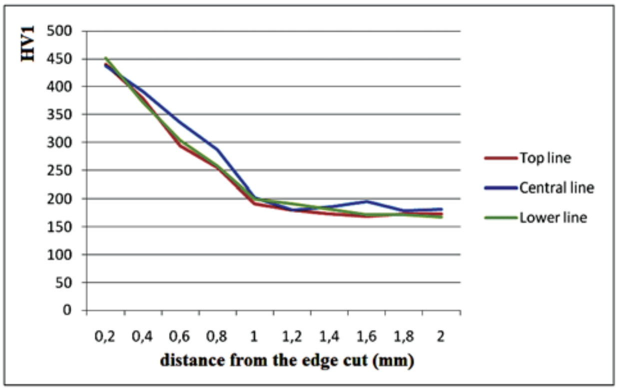

Figure 7 *Microhardness measurements after the plasma cutting at a thickness of 15 mm*
Slika 7. *Rezultati mjerenja tvrdoće nakon rezanja plazmom pri debljini 15 mm*

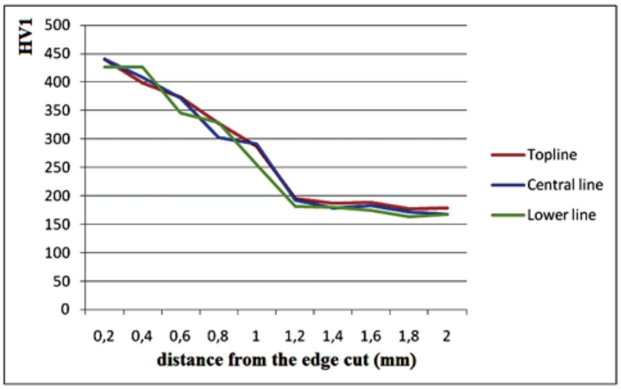

Figure 8 *Microhardness measurements after the plasma cutting at a thickness of 20 mm*
Slika 8. *Rezultati mjerenja tvrdoće nakon rezanja plazmom pri debljini 20 mm*

Also in this case the samples were subjected to metallographic analysis. The basic material is of the ferritic – perlitic structure. When plasma cutting, a displacement is observed (similar to laser and oxygen cutting) of the transformation temperatures A_1–A_3 to the higher temperatures than the equilibrium and the greater this displacement is, the higher the heating rate is.

The HAZ is formed by a narrow high heating zone having a high content of polyedric ferrite, where some micro cracks have occurred due to the stress caused by volume changes. The primary cause of the formation of hot cracking is a reduction of the deformation ability of individual grains and a decrease of the cohesion of grain boundaries at high temperatures during the acting of tensile stress and deformation speed. Furthermore runs through the zone of normalization annealing with a fine-grain structure and a significantly wider zone of the partial recrystallisation. The grain refinement results in the quality improvement (higher ductility, strength, toughness, less internal tension). Despite the significant increase in microhardness when plasma and laser cutting, with values of microhardness approaching martensitic structure (a martensite structure is difficult to be distinguished by a light microscope), its local occurrence is a subject being further investigated. The martensitic structure significantly complicates the mechanical treatment of cutting surfaces and increases the tendency of cold cracking in steel (Fig. 9).

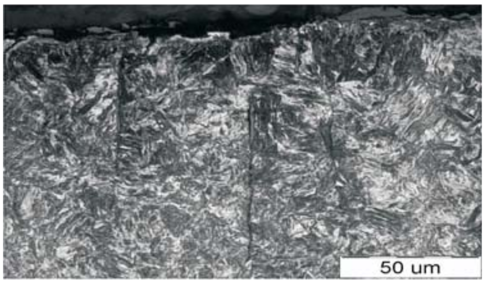

Figure 9 *The HAZ transition after the plasma cutting – magnification* 500×
Slika 9. *Prijelaz ZUT-a nakon rezanja plazmom – povećanje* 500×

The evaluation of the heat affected zone after the laser cutting was based on the changes in microhardness as well as in microstructure changes. The microhardness measurements according to Vickers showed a narrow heat affected zone [20, 21]. The given measurements were carried out similarly as in previous cases and thus in three lines (through the heat affected zone to the zone of the basic material). There is an increase in microhardness for each thickness, and thus from the zone of the basic material through the heat affected zone. The largest increase occurred at the thickness of 20 mm by an average of 200 HV1 and it was in a depth of 0,5 mm from the cutting edge. At a thickness of 15 mm there was a significantly smaller increase of 95 HV1 with a depth of the HAZ of 0,4 mm from the cutting edge. In the sample with a thickness of 10 mm there was again an increase in microhardness of 160 HV1 with a depth of the HAZ of 0,3 mm from the cutting edge (Fig. 10, 11, 12).

The metallographic analysis confirmed the formation of a favorable structure and also the HAZ in terms of its width as well as its crystallography structure with the changes in structures when passing through the zone of the basic material into the heat affected zone. The microstructure in a narrow zone within the high heated zone was created mainly by polyedric ferrite, ferrite excluded at the original austenitic grains and acicular ferrite.

The presence of these modifications is associated with a local increase in strength (apparent at microhardness investigation in the corresponding field). Furthermore runs through the zone of the normalization annealing, with a fine-grained ferritic-pearlitic polyedric structure. In the area of the partial recrystallisation there is a transformed flaked perlite (Fig. 13), [20, 21].

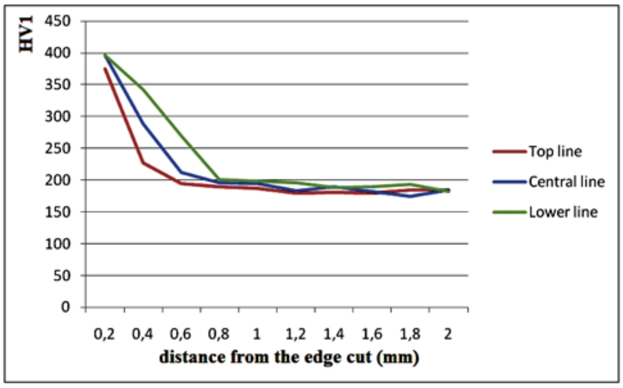

Figure 10 *Microhardness measurements after the laser cutting at a thickness of 10 mm*
Slika 10. *Rezultati mjerenja tvrdoće nakon rezanja laserom pri debljini 10 mm*

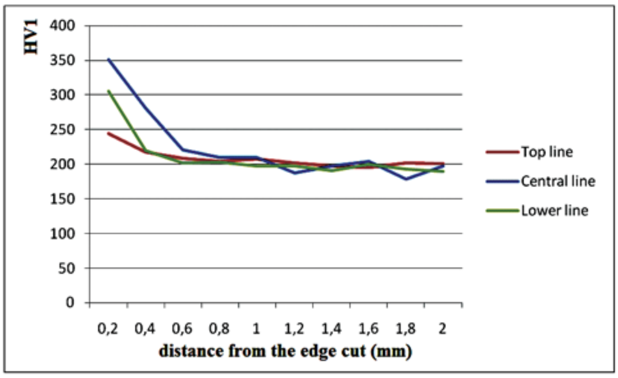

Figure 11 *Microhardness measurements after the laser cutting at a thickness of 15 mm*
Slika 11. *Rezultati mjerenja tvrdoće nakon rezanja laserom pri debljini 15 mm*

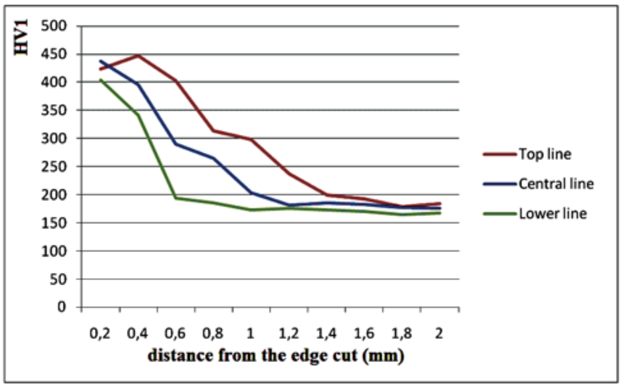

Figure 12 *Microhardness measurements after the laser cutting at a thickness of 20 mm*
Slika 12. *Rezultati mjerenja tvrdoće nakon rezanja laserom pri debljini 20 mm*

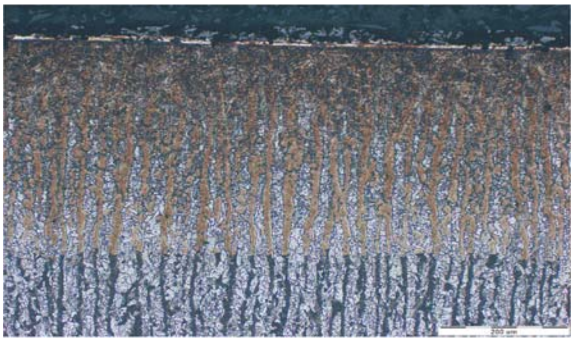

Figure 13 *The HAZ transition after the laser cutting – magnification* 100×
Slika 13. *Prijelaz ZUT-a nakon rezanja laserom – povećanje* 100×

5
Conclusion
Zaključak

The results obtained in this comparison of different material cutting technologies in terms of their impact on the size of the achieved heat affected zone can be summarized as follows:

- The smallest heat affected zone (that has been evaluated on the basis of microhardness measurements and metallographic analysis) was achieved after the laser cutting, whereas there were no large differences when comparing with different thicknesses of material, and the values of microhardness were comparable to the plasma cutting.
- The largest heat affected zone was achieved after the oxygen cutting, whereas the half values of microhardness were achieved compared to plasma or laser.
- Within the heat affected zone some structural changes have occurred (steel of the type EN S355J0 is a metal with a polymorphic transformation).
- The metallographic section shows the phase transformations, from the high temperature zone, zone of normalization, partial recrystallization and the basic material zone, which confirmed the presence of favorable structures and heat affected zone in terms of its width as well as its crystallography structure.
- After the plasma cutting some microcracks were observed due to the stress caused by the volume changes.

Acknowledgments
Zahvale

The work has been supported by CEEPUS program CII-PL-0007-05-0910 at the Kielce University of Technology in Poland.

7
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