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Influence of Cutting Parameters and Plasma Cutting Mode on Cutting Quality and Process Noise

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Plasma cutting is an ever-evolving method of industrial cutting of materials. Like all modern methods, it must meet the requirements for the quality of the cut, but also the hygiene and safety regulations set by European legislation. New ways are being sought to reduce process noise while improving the quality of the cutting surface. The article aims to compare two cutting modes (Contour Cut and Silent Cut) in terms of both the quality of the cut (roughness of the cutting surface, size of the heat affected area, perpendicularity and bevel angle of the cutting surface) and in terms of noise of the cutting process. The results in the article clearly show that the use of the Silent Cut mode has a demonstrably positive effect on the level of noise produced but also on the quality of the cut.

Keywords: Plasma Cutting, Cutting Quality, Noise, Roughness of the Cutting Surface, Hardness

1 Intruduction

Thermal separation of materials can be included in material preparation operations within engineering production. By this term we mean cutting technology, working on the principles of local melting, combustion or evaporation, or a combination of these phenomena, where the energy needed to initialize the process and its course is supplied by various heat sources. In general, thermal separation of materials can be applied to a range of structural materials: non-alloy and low-alloy steels, high-alloy steels and nickel-based alloys, non-ferrous metals and their alloys (e.g. aluminum, copper), highly reactive materials and their oxygen-sensitive alloys (such as magnesium or titanium), non-metallic materials (plastics, composites, wood, paper, glass). In industrial practice, three basic methods of thermal cutting with oxygen, plasma and laser are used [1].

Plasma began to be used industrially in the 1950s. Then plasma began to be used as one of the forms of thermal separation of the material and gradually this method is developed. Leading manufacturers of plasma sources are constantly improving the method of plasma cutting in various areas. The plasma cutting modes themselves are constantly being improved in terms of cutting quality, work productivity, accessory life and also with regard to increasing the hygienic demands on the process. Plasma material separation technology is very often used today for the preparation and separation of material. E.g. for the treatment of welded surfaces before welding technology, where it is necessary to monitor the effect on the change of structure and mechanical properties. The structure and geometry alteration occurring after parting strongly affect cutting forces during the following for example milling operations [2]. Today, specialized machines are used for metal cutting, which use various cutting methods, for example laser [3] or plasma beam. Plasma cutting not only takes into account noise, but also it is necessary to achieve the required quality of cut, assessed according to EN ISO 9013 [4]. In accordance with this standard, the quality of the cut can be evaluated by various parameters such as roughness or perpendicularity deviation. Other requirements may be based, for example, on product standards such as EN 1090, which includes a requirement to check the change in hardness of the cutting edge. The surface roughness and the conicity are mainly affected by the cutting height, the heat affected zone is mainly influenced by the cutting current [5] and other parameters such as cutting speed.

Many authors deal with the quality of the cut. E.g. Nedić et al. [6] relates the roughness parameters (Ra and Rtm) and the size of the cutting current. He came to the conclusion that the roughness of the cutting surface decreases with increasing cutting current. The influence of pressure and distance between the nozzle exit and cutted material on the roughness of the cutting edge did not prove. In contrast, Masoudi et al [7] confirm the increasing roughness of the cutting surface with increasing cutting speed and cutting current. When comparing plasma and laser cutting methods [8], plasma cut edges have larger changes in the HAZ microstructure. In terms of the roughness of the cutting edge, the plasma parameter Ra increases with increasing cutting speed, while it decreases with laser cutting. The quality of the cut can also be influenced by the way of stabilization of the plasma arc or also by the design of the torch [9], while better roughness is achieved at oblique cut. Even a slight arc constriction with a nozzle leads to a substantial plasma temperature rise, increases the arc voltage (and its power) and makes the arc more directional [10]. This also affects the surface quality of the cutting edge.

Due to the high density and energy flow during plasma cutting, the noise level can reach more than 100 dB. Manufacturers of modern cutting equipment try to reduce this load on the working environment as much as possible. The article considers two cutting modes from Kjellberg (Contour Cut and Silent Cut). Contour Cut stands for the precise cutting of mild steel. When cutting small contours, narrow bars and especially small holes with a diameter to thickness ratio of 1: 1 an outstanding cut quality is achieved. Smooth cut surfaces and sharp cut edges reduce time-consuming aftertreatment. Thus, productivity increases while costs are reduced [11]. Silent Cut technology is an optimized Contour Cut technology that offers a solution to significantly reduce noise during cutting. Silent Cut technology reduces the sound pressure level by up to 15 dB during material cutting in the current range between 60 and 160 A (i.e. for cut thicknesses from 3 to 40 mm). Decreasing the sound level by 10 decibels is perceived by the human ear as half the volume value. Silent Cut is thus considered to be a technology that contributes significantly to the protection of health and safety when working with high quality cuts [12].

2 Material and Methods

A steel sheet S 235JR with a thickness of 10 mm was used as the cut material. It is a structural steel of the usual quality. In addition to strength, this steel is further characterized by other properties such as plasticity, ductility, toughness and machinability. This allows a wide range of steel applications in terms of safety, structural rigidity and manufacturing requirements [13]. The stated range of properties of structural steel allows its wide use in construction. These steels are used for thin-walled machine structures, less stressed welded structures, as well as for welded, bolted and riveted structures for the construction of buildings, cranes, bridges, etc. It is also used for less stressed machine parts and supporting structures of machines. For this steel, only normalization annealing is used, which serves to give the steel a homogeneous and fine-grained structure, it is not intended for further heat treatment. In Tab. 1 is the chemical composition of steel and its mechanical properties. In Fig. 1 is a characteristic microstructure of the base material (BM). In Fig. 2 is the heat affected zone (HAZ). S235JR steel is well weldable by all usual methods. Due to its good hot and cold formability, this material is suitable for bending, pressing and drawing.

Tab. 1 *Chemical composition [wt%]) and mechanical properties*

C [%]	Mn [%]	Si [%]	P [%]	S [%]	N [%]	min. Re_H [MPa]	Rm [MPa]	min A [%]
0.17	1.4	-	0.045	0.045	0.009	235	360 - 510	26

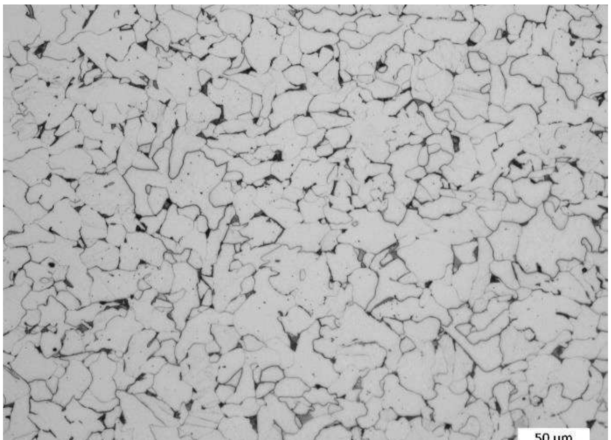

Fig. 1 *Microstructure of the base material, etchant Nital 2 %, magnification 200x*

After the cutting process, the cutting edge surface was analyzed for roughness, shape and perpendicularity of the cutting edge. Furthermore, the microstructure, the size of the HAZ were evaluated and, last but not least, the noise of the cutting process was measured - all for the two above-mentioned cutting modes: Contour cut and Silent Cut. The method and location of roughness measurement was determined in accordance with EN 1090-2 Annex D: Procedure for checking the ability of the automated thermal cutting process.

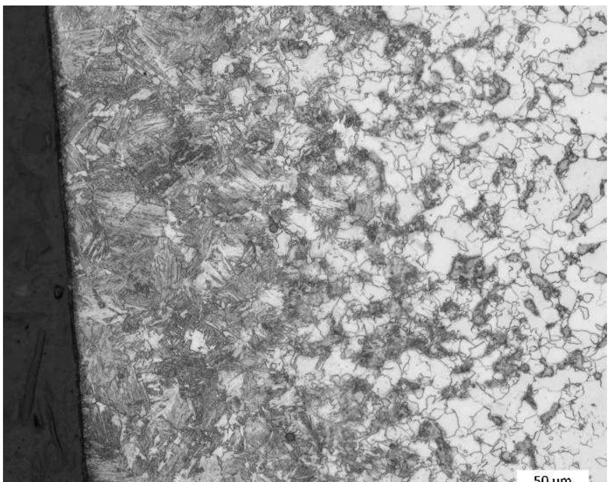

Fig. 2 *Microstructure of heat affected zone HAZ, etchant Nital 2 %, magnification 200x*

An AxioObserver metallographic inverted microscope (from Zeiss) was used to evaluate the perpendicularity and size of the heat affected area (HAZ). The determined perpendicularity deviation "u" was compared with the table of the tolerance field according to standard EN 1090-2 (execution of steel structures and aluminum structures-Part 2: Technical requirements for steel structures) [14].

A Bruel and Kjaer measuring instrument, type Pulse B&K Pulse 356 - B -140 and 5 microphones arranged around the CNC machine were used to measure the noise (Fig. 3). All sound level meters were located 2 m away and at a height of 1.5 m from the cutting torch. The frequency of sound that affects a person, the human hearing perceives with different sensitivity. For this reason, it is necessary to frequency adjust the linearly measured acoustic signal so that its frequency response corresponds to how it is perceived by humans. For this purpose, the sound level meters are equipped with a so-called weight filter. Values corrected by weight filter A (i.e. what the human ear hears) and uncorrected values were used to measure noise. Weight filter A is the most widely used filter for measuring acoustic signals.

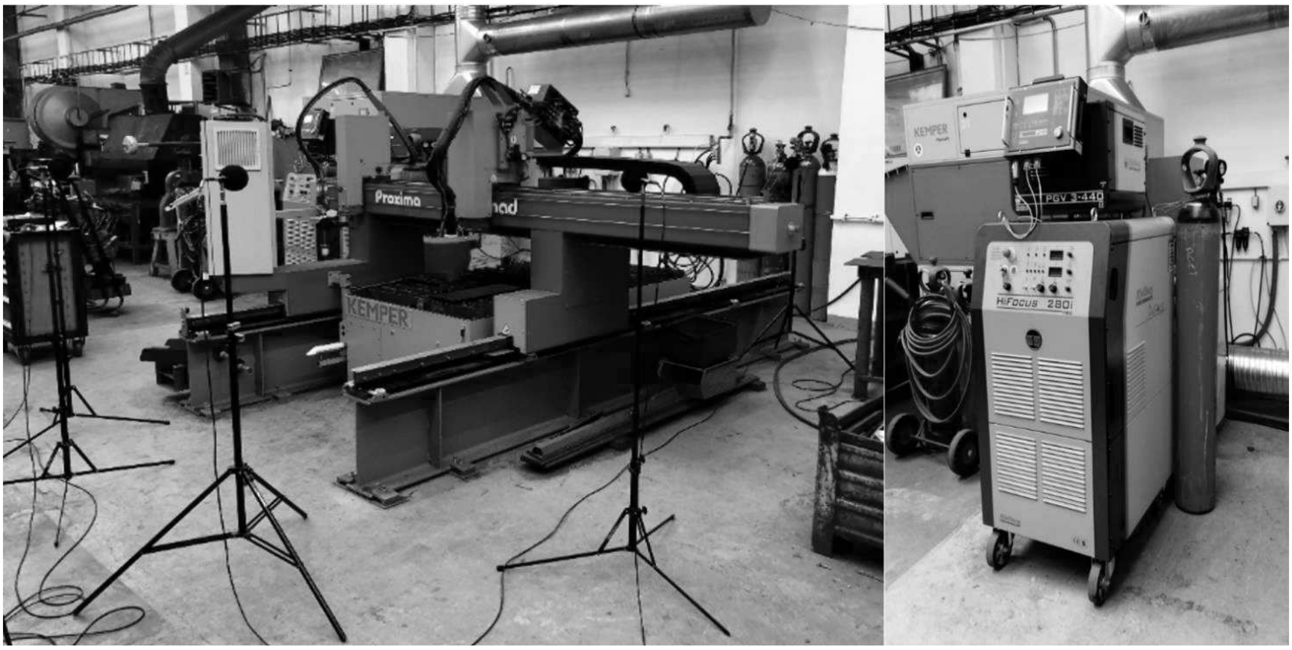

Fig. 3 *Location of microphones around the cutting device (left) and used plasma source (right)*

3 Experimental

Samples were cut from S235 steel at different cutting speeds, at different angles and using different cutting modes (where the accessories of the cutting torches were replaced, more precisely the torch nozzles). The aim was to evaluate the effect of changes in cutting parameters (cutting speeds), changes in cutting angle and path (straight, oblique cut and radius cut) and changes in cutting mode (Contour cut and Silent from Kjellberg). The comparison was evaluated in terms of the quality of the cuts (roughness of the cutting surface, perpendicularity of the cut) and the influence of the structure (HAZ size). Furthermore, the noise of the plasma device during cutting was measured for all sections.

A Vanad Proxima CNC portal cutting machine with a Kjellberg Firstenwalde HiFocus 280i neo plasma source was used for cutting. The cutting parameters were set automatically according to the optimal parameters set by the manufacturer of the cutting source depending on the thickness and type of material. Two types of cutting modes (Contour Cut and Silent Cut) were used. The current load (cutting current) was always set to 90 A for comparability of results. The cutting speed was first set to the value recommended by the manufacturer. Subsequently, the speed was reduced and increased by 30% in order to evaluate the effect of cutting parameters (represented by cutting speeds). When using the Silent Cut torch, the material was not cut as the speed increased. For this reason, the speed was increased by only 15%. However, even then the result was not sufficient. Therefore, the speed was reduced by 15% from the optimum value.

In the end, a combination of cutting speeds was chosen for the Silet Cut mode: optimal, reduced by 30% and reduced by 15%. Cutting speeds are given in Tab. 2. For optimal values of the cutting speed, the angle of inclination (straight, oblique - 30%) and the path (line, radius) were changed for both types of torches. Oxygen was used as the plasma gas and a mixture of oxygen and compressed air was used as the vortex gas.

Tab. 2 *Cutting speed v_c [m·min⁻¹] for individual samples*

Torch path/angle	line / straight (v_{opt})	line / straight ($v_{-30\ \%}$)	line / straight	line / oblique (30°)	radius /straight
Contour Cut	**C1**	**C2**	**C3** ($v_{+30\ \%}$)	**C4**	**C5**
	1.6	1.1	2.1	1.6	1.6
Silent Cut	**S1**	**S2**	**S3** ($v_{-15\ \%}$)	**S4**	**S5**
	2.5	1.7	2.1	2.5	2.5

The roughness was measured perpendicular to the cutting direction, always at a maximum distance of 40 mm. Five consecutive roughness measurements were performed on each sample in order to evaluate the average height of the Rz5 profile. Roughness was measured with a Mitutoyo SJ-30 roughness tester for each sample five times at different points on the cutting surface [15].

When measuring noise, in the first step, the background noise was measured with the plasma device switched off. As a next step, it was measured with the plasma device switched on but with the suction switched off. Both measured values were then used to correct the individual sound tracks recorded when cutting the samples. A total of 9 audio tracks were recorded, each on 5 microphones. Each soundtrack was recorded in third octave bands in the range of 125 to 20,000 Hz. From these values for each soundtrack, the resulting value of the acoustic sound level Lp was evaluated. The acoustic sound Lp is calculated according to Equation 1. The value of the acoustic sound level Lp_A corrected by the weight filter *A* was also evaluated. Lp_A was calculated according to Equation 2. The averages of the values from all five microphones were always used as evaluation values. Thus, 9 values of acoustic sound without correction were measured for all cutting speeds, background, machine noise and machine noise with suction.

$$Lp = 10 \times \log_{10} 10^{(0.1 \cdot n1)} + \cdots + 10 \times \log_{10} 10^{(0.1 \cdot n31)} \tag{1}$$

$$LpA = 10 \times \log_{10} 10^{(0.1 \cdot (n1 + Ky1))} + \cdots + 10 \times \log_{10} 10^{(0.1 \cdot (n31 + Ky31))} \tag{2}$$

Where: x ……. the value of the soundtrack in the third octave band

Ky …... weight filter A value

Furthermore, the noise value of the cutting process itself was evaluated, without the influence of the surrounding environment. Noise was measured up to 0.1 s after ignition of the arc. In practice, although the greatest noise is generated during arc ignition, material burning and change of cutting direction, in this experiment the evaluation of measurements was performed under steady cutting conditions - to capture changes between torch angle settings and evaluate the effect of cutting conditions on noise.

4 Results and Discussion

The roughness of the cutting surface as a function of the cutting speed is shown in Fig. 4. From Fig.4 and Fig.5 it can be seen that on a straight path in the case of the Contour Cut torch, the roughness of the cutting surface increases rapidly with the cutting speed (from Rz = 4.5 µm at 1.1 m·min⁻¹ to Rz = 10.6 µm at 2.1 m·min⁻¹).

In the case of the Silent Cut torch, the roughness values remain at similar values. The reduction in cutting speed has no particular effect on the roughness. At the same time, the roughnesses at all speeds are below the roughness values measured on the cut when using the Contour Cut torch. At lower speeds the difference is small, but at optimal speeds the change is significant.

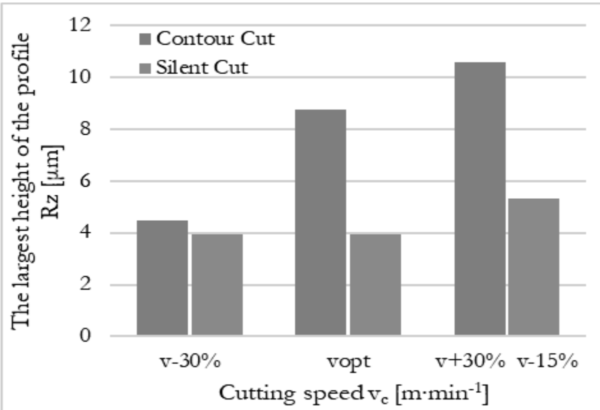

Fig. 4 *Roughness (the largest height of the profile Rz) of the cutting surface depending on the cutting speed*

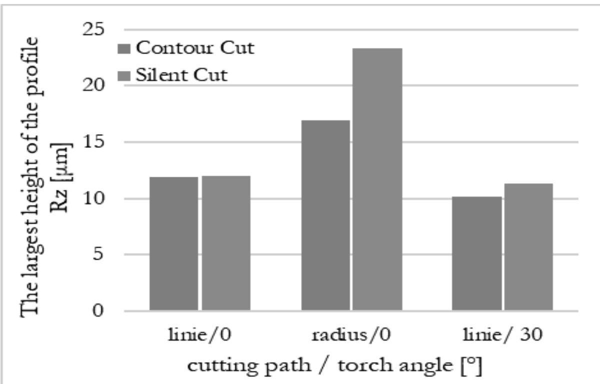

Fig. 5 *Roughness (The largest height of the profile Rz) of the cutting surface depending on the cutting path and the angle of inclination of the torch at the optimum speed v_{opt} = 1.6 m·min⁻¹*

The dependences of the shape of the torch path, the angle of inclination and the roughness of the cutting surface at the optimum speed $v_{opt} = 1.6\ m \cdot min^{-1}$ are shown in Fig. 5. It can be seen that the oblique cut (torch inclination angle 30°) has essentially no effect on the roughness (as confirmed by the results Masoudi [7] but contradicts the results of Anakhov et al [9]). Another situation occurs in the case of a radius cut. In both cases, there was a significant increase in the roughness of the cutting surface. For the Silent Cut torch, this change is even more pronounced.

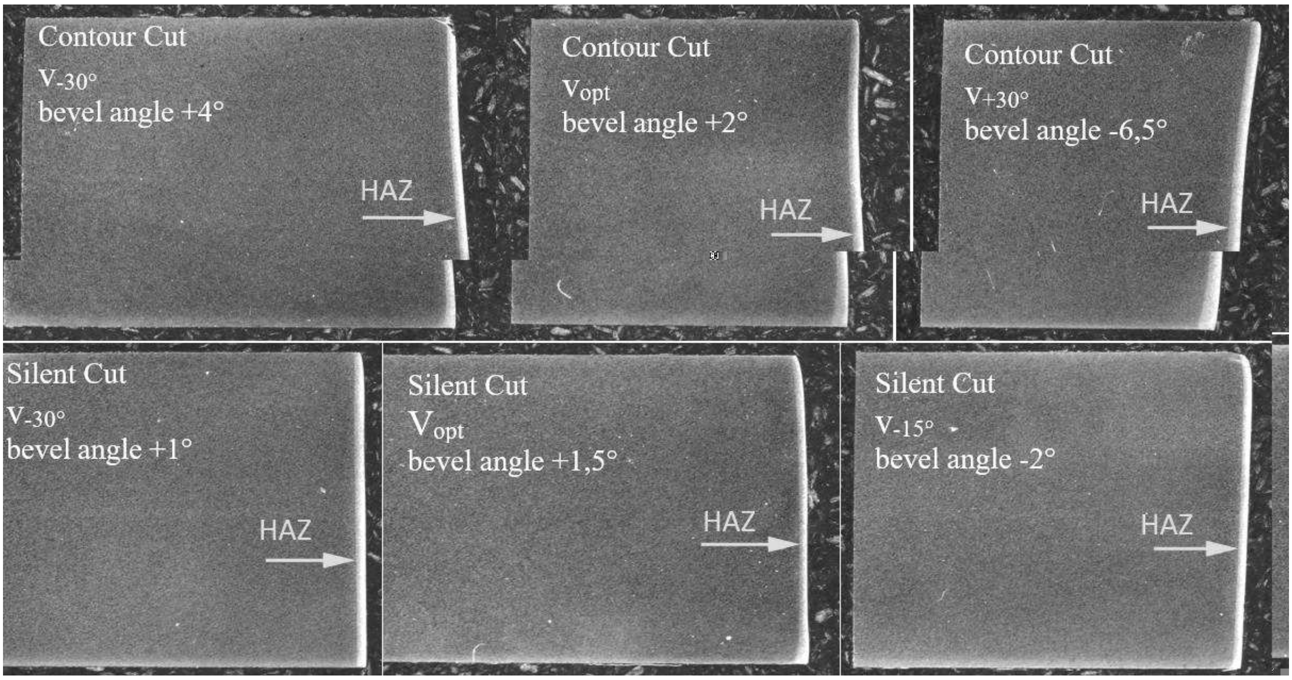

Fig. 6 *Cross-section macrostructure and bevel angle of the cutting surface for both types of torches at different cutting speeds*

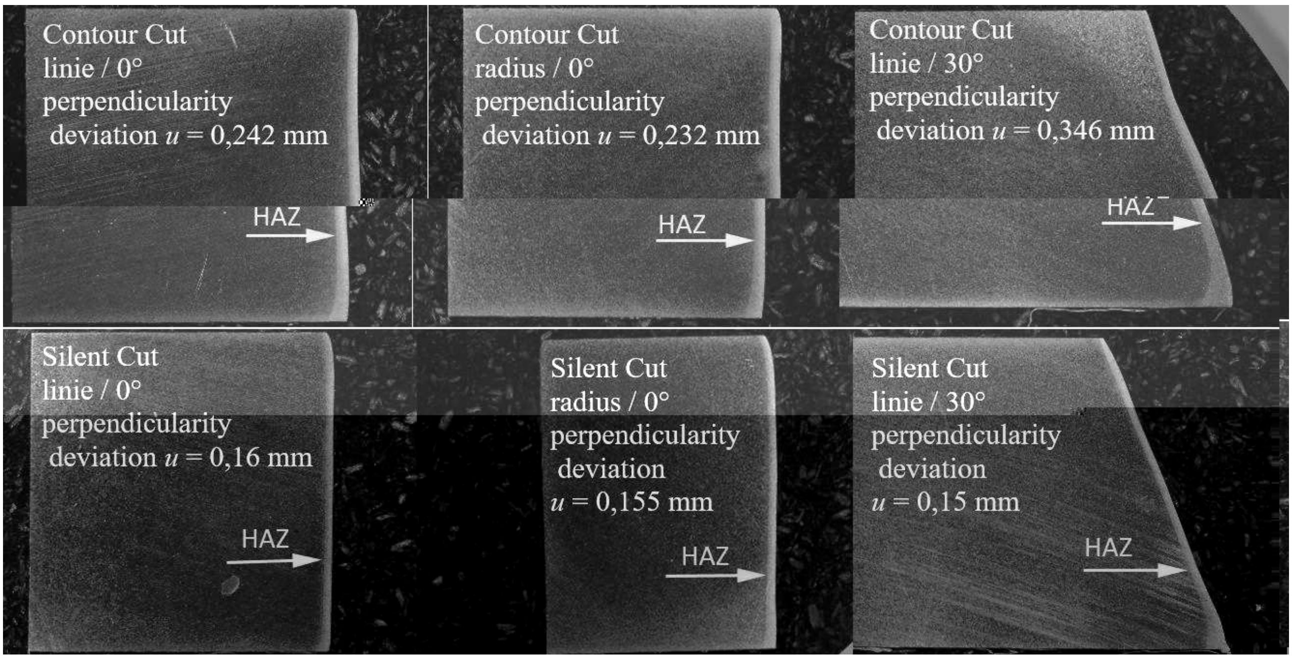

Fig. 7 *Cross-section macrostructure and perpendicularity deviation "u" of the cutting surface for both types of torches at different paths and angles of rotation of the torch*

The macroscopic test (Fig. 6 and Fig. 7) shows the effect of the cutting speed and the flatness of the cut. It can be said that the use of the Silent Cut torch leads to better results at all speeds. The cut does not wave, it is straight, with minimal deviation. The best cut was achieved at the lowest speeds, although compared to the Contour Cut torch, this speed is already above the optimum value. At the optimum speed, the result of cutting with a straight path torch is significantly better. The same result was achieved on the radius, as well as on the oblique cut.

When using the Contour Cut torch, oxides formed on the underside of the material being cut. The oxides were not firmly attached to the base material. They were easily removed. At cutting speeds of 1.6 m·min^{-1} and speed of 1.1 m·min^{-1}, the oxides were uniform over the entire cutting area. When a cutting speed higher than the optimum speed specified by the equipment manufacturer is used, oxides were hardly formed on the material to be cut. Visible oxides were found in the last part of the section.

In the Silent Cut method, the oxides on the surface differed significantly. Unlike the Contour Cut method, the oxides had a different shape. Although they were significantly smaller, they were also harder to remove. Drops of molten material remained on the lower edge of the cut. The best result was achieved when cutting at a speed of 1.7 m·min^{-1}, where no oxides were formed at all. At other speeds, the oxides had a similar shape. They were firmly bonded to the base material at the bottom edge of the cut.

As can be seen from the macrostructures of the individual sections (Fig. 6 and Fig. 7), the HAZ was wider when using the Con-tour Cut torch. This is confirmed by the graph in Fig.8. It can be seen from the graph that the HAZ is widest at the lower edge of the section. This phenomenon is very pronounced with the Contour Cut torch. When using the Contour Cut torch, the size of the HAZ increases slightly with the cutting speed, which corresponds to the results of Stancekova et al. [16]. Conversely, when using a Silent Cut torch, surprisingly, the size of the HAZ decreases slightly with the cutting speed.

From Fig. 9 it can be seen that the size of the HAZ is essentially unaffected by the path of the torch (line, radius). A torch angle of 30° leads to an increase in HAZ size of up to 40 %. And when using the Silent Cut torch, this increase is lower. Last but not least, cutting noise was measured. From the graph in Fig. 10 it can be seen that the path of the torch (line/radius) has little effect on the noise level during cutting. However, the type of torch has a big effect. Demonstrably better results (less noise) were achieved using the Silent Cut mode. In Fig. 11 shows not only the dependence on the torch used (using a Silent Cut torch reduces the process noise by up to 5 dB), but also the effect of speed. The process noise decreases with increasing speed.

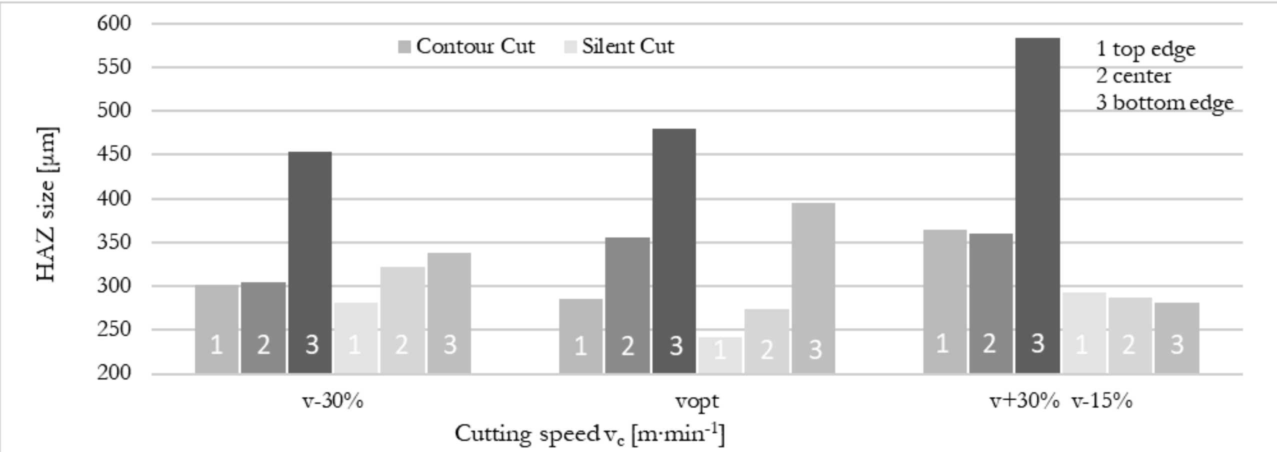

Fig. 8 *Size of heat affected zone (HAZ) depending on the cutting speed, for both types of torches*

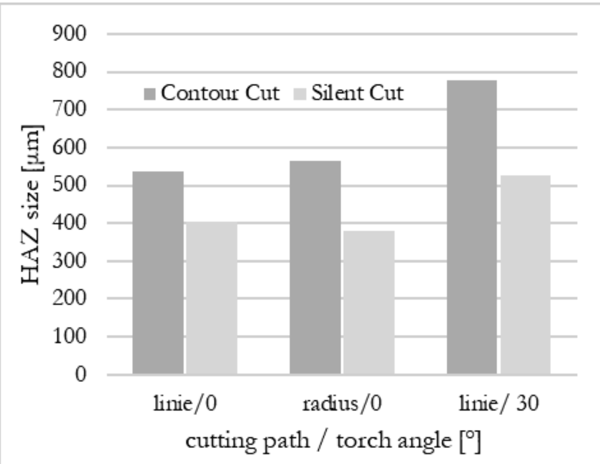

Fig. 9 *Size of heat affected zone depending on the path and angle of inclination of the torch, for both types of torches*

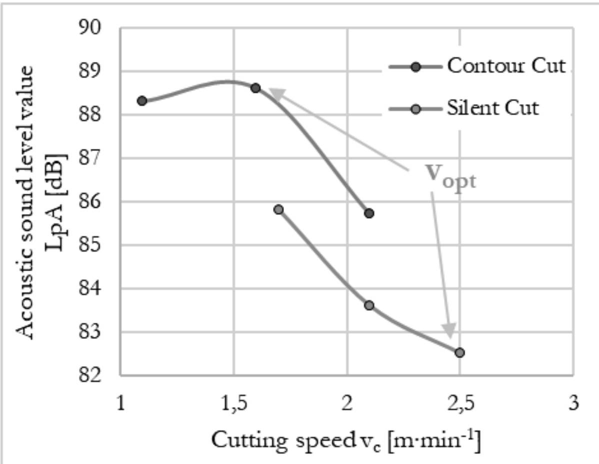

Fig. 10 *Average values of the sound level Lp_A depending on the cutting speed*