KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Ignas Kudžma

EVALUATION OF BLANKS' QUALITY FORMED BY PLASMA CUTTING

Master's Degree Final Project

Supervisor
Assoc. prof. dr. Saulius Baskutis

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Industrial engineering and management (code 621H77003)

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KAUNAS, 2017

KAUNAS UNIVERSITY OF TECHNOLOGY

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(Title and code of study programme)

" Evaluation of Blanks' Quality Formed by Plasma Cutting "

DECLARATION OF ACADEMIC INTEGRITY

02 June 2017

Kaunas

I confirm that the final project of mine, **Ignas Kudžma**, on the subject "Evaluation of Blanks' Quality Formed by Plasma Cutting" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarized from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this thesis.

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Approved:
Head of Production engineering Department

____
(Signature, date)

Kazimieras Juzėnas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Evaluation of blanks' quality formed by plasma cutting.

Approved by the Dean Order No.V25-11-8, 21 April 2017

2. Aim of the project

Analyze how different plasma arc cutting parameters affects quality of blanks.

3. Structure of the project

- Summary in English and Lithuanian languages;
- Introduction;
- Review of related sources;
- Research part;
- Results;
- Conclusions;
- References;
- Annexes.

4. Requirements and conditions

- The project must be prepared according requirements and on time.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2017 June 2nd.

Student ______Ignas Kudžma_______ __ ______________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor Assoc. prof. dr. Saulius Baskutis ______________________
(*Position, Name, Surname*) (*Signature, date*)

Ignas Kudžma. Evaluation of blanks' quality formed by plasma cutting. Master's Final Project / supervisor assoc. prof. dr. Saulius Baskutis; Faculty of mechanical engineering and design, Kaunas University of Technology.

Research field and area: Technological science, Production engineering.

Keywords: Plasma arc cutting, cutting speed, amperage, hardness, heat affected zone, roughness.

Kaunas, 2017. 58 p.

SUMMARY

Plasma arc cutting is one of the most common way to prepare blanks in our days. This sheets cutting method is relatively fast, cheap and ensures quite good quality of cut. However, this type of cutting has negative impact on material such as material hardening and heat affected zone near the cut edge, what leads to changes of microstructure or micro cracks.

This master's project reveals what impact on blank quality can be made by changing parameters of plasma arc cutting. Several blanks of steel S235JR, S235JR+N and steel AISI 316 L were prepared by changing cutting parameters. To analyse relation between cutting parameters and cut quality, the measurements of hardness near the cut and surface roughness were done by using each blank. Also, there were the measurement investigations of heat affected zone done.

The investigations and measurements reveals that by changing cutting parameters it is possible to achieve variations of heat affected zone, as well as variations of cut surface roughness. Also the investigations show that material near the cut edge becomes much harder than base material and this hardness reduces when the distance from the cut edge increases.

Ignas Kudžma. Plazmos srautu atpjautų ruošinių kokybės tyrimas. Magistro baigiamasis projektas / vadovas doc. dr. Saulius Baskutis; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Mokslo kryptis ir sritis: Technologijos mokslas, gamybos inžinerija.

Reikšminiai žodžiai: *Pjovimas plazmos srautu, pjovimo greitis, elektros srovė, kietumas, karščio paveikta zona, šiurkštumas.*

Kaunas, 2017. 58 p.

SANTRAUKA

Pjovimas plazmos srautu yra vienas iš dažniausiai naudojamų būdų ruošinių paruošimui. Šis metodas yra sąlyginai greitas, pigus ir užtikrina gana gerą pjūvio kokybę. Nepaisant to šis pjovimo būdas turi ir neigiamus poveikius metalui, tokius kaip medžiagos užsikietinimas ir karščio paveiktos zonos atsiradimas, kurie sukelia medžiagos mikro struktūros pakyčius ar netgi mikro įtrūkimus.

Šis magistro tiriamasis projektas atskleidžia kokį poveikį ruošinių kokybei turi pjovimo parametrų pasikeitimai. Keliolika bandinių iš plieno S235JR, S235JR+N ir AISI 316 L buvo išpjauti keičiant pjovimo parametrus. Ištirti priklausomybei tarp pjovimo parametrų ir pjūvio kokybės buvo atlikti kietumo matavimai šalia pjūvio ir pjūvio šiurštumo matavimai su kiekvienu iš bandinių. Taip pat buvo atliktas karšio pavaiktos zonos tyrimas.

Tyrimai ir matavimai atskleidė, kad keičiant pjovimo parametrus galima pasiekti skirtingų rezutatų karščio paveiktos zonos matavimuose, taip pat kaip ir rezultatų pjūvio šiurkštumo matavimuose. Taip pat tyrimai parodė, kad medžiaga šalia pjūvio tampa kietesnė negu pagrindinė medžiaga ir kietumas mažėja tolstant nuo pjūvio.

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INTRODUCTION

In our days, steel plates are used in many different purposes. Many of them is used in structures for constructions, technological equipment, machinery and etc. By using modern CNC cutting machines is very easy to prepare required dimensions and form plates, even preparation for welding can be done by using CNC cutting machines. One of the most popular way to prepare blanks or parts from plates is plasma arc cutting. Since beginning of development of this process many variations of this process was created until high tolerance plasma was invented. This type of plasma cutting machines can be found in most of medium and large size steel workshops.

High tolerance plasma have features such as narrow cut kerf, relative high cutting speed and dimensional tolerances, ability to cut through thick metals. In many cases plasma arc cutting is used for blanks preparation for machining operations such as turning or milling. Because of this, fact that cut surface become harder than base material is very important. Hardened surface have negative impact for machining, it cause tools wear and increased machining time.

In case when parts cut by plasma is used as a finished part without any machining very important is surface roughness, because sometimes parts functionality depends on it. Plasma arc cutting is a process when material at cut zone is melted and blown away to create cut. Heat creates specific zone near cut where material microstructure is quite different than its base material, this zone is called heat affected zone. HAZ can cause loss of part mechanical properties and cause micro cracks on cut surface.

Seeking to reveal how features such hardness, surface roughness and heat affected zone is related with cutting parameters this research project was done. Different grades and thicknesses of materials such as steel S235JR t=15, S235JR+N t=5 and AISI 316 L t=6 is in scope of this research. Blanks preparation was done in company AB “Axis Industries” by using high tolerance plasma arc cutting machine with CNC controller. All of researches and measurements was done in Kaunas University of Technology, faculty of mechanical engineering and design by using inventory such hardness tester, roughness tester, polishing machine, microscope and others.

Aim of this research project is:

Analyze how different plasma arc cutting parameters affects quality of blanks.

Main tasks of this research work is:

1. Evaluate materials hardness near cut and hardness of core material after plasma arc cutting;

2. Reveal tendency between distance from cut and material hardness after plasma arc cutting;
3. Analyze relation between cutting speed and width of heat affected zone;
4. Analyze relation between cutting amperage and width of heat affected zone;
5. Reveal relation between cutting speed and surface roughness;
6. Reveal relation between cutting amperage and surface roughness;
7. Provide recommendations for plasma arc cutting.

1. THEORETICAL BACKGROUND

1.1 History of plasma arc cutting

Development of plasma arc procedures starts in 1941 during WWII. Because of shortage of time U.S. defence industry was looking for better and faster procedures to join light metals for airplanes and other vehicles manufacturing. At that time a new welding procedure (TIG) was born. The main principle of TIG welding is that electric arc is used to melt metal and in inert gas save molted metal pool from picking up oxygen from air around it. The weld is formed by adding filler in weld pool [1].

By 1950 TIG (Tungsten Inert Gas) establish itself as a method for exotic materials welding with high quality. During future developments scientists at Union Carbide's welding laboratory discovered that reduced nozzle opening constricted the electric arc and gas and also increased its speed and its resistive heat. Temperature and voltage of the arc rose significantly, and the momentum of the ionised and non-ionised gas removed the molten puddle. It shows, that instead of welding, this process can be used for metal cutting by plasma jet [1; 2].

In the late 1960s plasma cutting technology showed that it can be used in commercial applications, but advantages of that technology cost a lot and not every company were able to make an extremely expensive investment at that time. Companies which invested received high profits because of the ability to cut metal more accurate and more quick than others. Today plasma cutting equipment is highly used in almost every workshop to cut mild steel, stainless steel, high hardness metals, aluminum, copper and other metals [2-4].

1.2. Principle of plasma arc cutting

The main principle how conventional plasma cutters work is that an electric arc goes through the gas passing through a nozzle. Various gases can be used for that, such as nitrogen, argon, oxygen and etc. This rises the temperature of the gas and gas enters the 4th state of matter known as plasma. Temperature of the plasma can reach over 20 000°C and the velocity can approach the speed of sound. Plasma gas flow is increased so that the deeply penetrating plasma jet cuts through the material and molten material is removed in the efflux plasma [5; 6].

Only electrically conductive metals can be cut by using plasma arc cutting. Electrically conductive gas transfers energy from an electrical power source through a plasma cutting torch to the materials being cut. Every PAC system must have three elements:

- power supply;
- arc starting circuit;
- cutting torch.

These elements provide electrical energy, ionization capability and control of the process. It is essential to ensure fast cutting with high quality on different materials. For the power supply constant current DC power source is used, open circle voltage is usually in range from 240 to 400 volts. The main purpose of power supply is to supply correct energy to maintain the plasma arc after ionization. The arc starting circuit generates high frequency AC power, normally voltage is between 5000 and 10000 volts and frequency is about 2 megahertz. This high voltage is needed to ionize the gas which produce the plasma. A torch is dedicated to hold the nozzle and electrode, also provides cooling to these parts. Graphical illustration of conventional plasma arc cutting process is shown in Fig. 1.1. [7; 8].

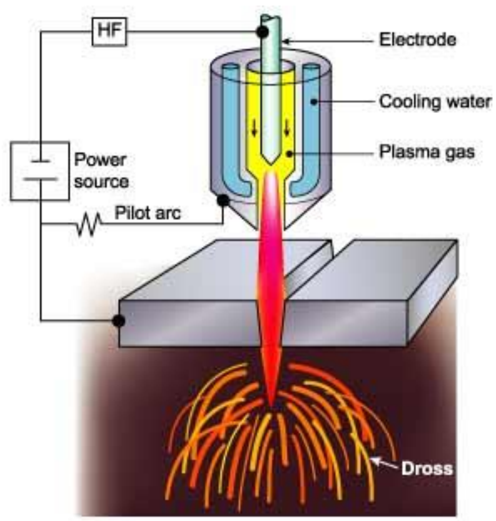

Fig. 1.1. The conventional plasma arc cutting process [6]

Advantages of conventional plasma:

- small risk of changing the shape of the metal (called distortion);
- precise cutting;
- slag-free cuts when working with aluminum, stainless steel and carbon steel;
- works in all positions;

- fast process;
- works across many types of metals;
- do not require gas cylinders.

Disadvantages of conventional plasma:

- creates a small bevel (7 degrees - approximate);
- risk of electrical shock, when not operating safely;
- requires clean air source;
- needs electricity to operate, so not completely portable;
- not cost effective for very thick steel [9].

1.3. Variations of plasma cutting process

Five variations of plasma cutting process exist [10]:

- dual gas plasma;
- water injection plasma;
- water shroud plasma;
- air plasma;
- high tolerance plasma.

1.3.1. Dual gas plasma

It operate almost the same as conventional system, the main difference is that there is secondary gas shield around the nozzle (Fig. 1.2.).

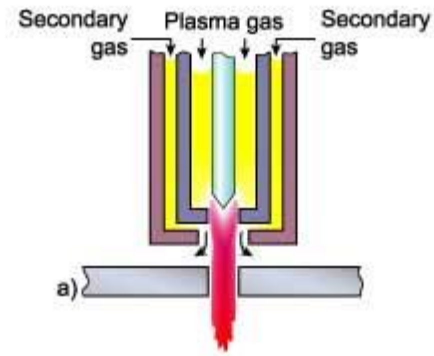

Fig. 1.2. Dual gas plasma [6]

The biggest benefit of this process is that secondary gas increases arc constriction and has more effective 'blowing away' of the dross. In this type of process primary gas is usually nitrogen and secondary shielding gas is selected depending on material that needs to be cut. For secondary shielding typically are used: air or oxygen for mild steel, carbon dioxide for stainless steel, and an argon/hydrogen mixture for aluminum. Using dual gas plasma cutting speed is higher than using conventional plasma cutting on mild steel. Cutting quality on mild steel is not good enough for many applications, but cutting stainless steel or aluminum quality is the same as in the conventional process [1,6;7;9;10].

The advantages compared with conventional plasma are:

- reduced risk of 'double arcing';
- higher cutting speeds;
- reduction in top edge rounding.

1.3.2. Water injection plasma

This type of plasma arc cutting process uses a symmetrical impinging water jet near the constricting nozzle orifice in order to constrict the further plasma flame (Fig. 1.3.).

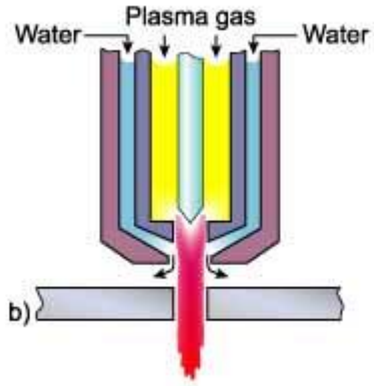

Fig. 1.3. Water injection plasma [6]

Water works as a shield and covers cutting area from surrounding atmosphere. Water constricts the arc and this lets to produce narrow, sharply defined cut with sharp corner. Because of the water dross elimination from the cutting area it is very efficient when cutting mild steel. By using this process plasma temperature reaches 30,000°C and speed is about speed of sound. Optimum cut quality is achieved by using one gas for all metals. The gas is nitrogen, as this gas has superior ability to transfer heat from the arc to work piece. It is more economical and efficient to use one kind of gas. Secondary function of water is to protect the nozzle from the intense heat of the arc. This also allows to implement some design innovation: the lower part of nozzle can be made of ceramic and it helps to prevent double arcing and extend lifetime of the nozzle [1;6;7;9-11].

The advantages compared with conventional plasma are:

- improvement in cut quality and squareness of cut;
- increased cutting speeds;
- less risk of 'double arcing';
- reduction in nozzle erosion.

1.3.3. Water shroud plasma

It is one of plasma arc cutting process where water is used instead of shield gas (Fig. 1.4.).

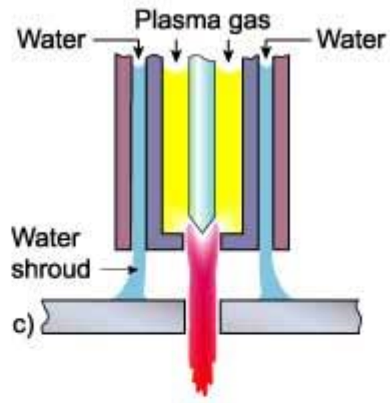

Fig. 1.4. Water shroud plasma [6]

It is possible to make a plasma cut even if work piece is submerged 50-75mm below the surface of the water. This type of process ensures better nozzle and workpiece cooling, also improves cut quality on stainless steel. Water shroud plasma is more silent than conventional plasma. Noise level of conventional plasma is about 115 dB, while water shroud reduces it to 96 dB. If cutting under water, noise level can be reduced from 52 to 85dB. This type of plasma do not increase constriction, squareness of the cut edge and speed [6;7;10].

Advantages:

- fume reduction;
- reduction in noise levels;
- improved nozzle life [6;7;10].

1.3.4. Air plasma

The gas used in plasma can be replaced by air, but in this case a special electrode is required, which is made of hafnium or zirconium and mounted in a coper holder (Fig. 1.5.).

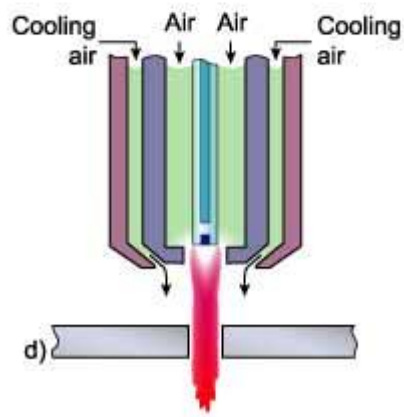

Fig. 1.5. Air plasma [6]

Air also provides a cooling function. This type of plasma has only one advantage: expensive gas is replaced by air. On the other hand, electrode for this plasma is more expensive than for the others [6,10].

1.3.5. High tolerance plasma

In order to improve PAC cut quality, high tolerance plasma arc cutting (HTPAC) was created. By using this type of plasma the quality of cut can compete with cuts made by laser systems, because this type of plasma operates with highly constricted plasma. In order to create more precise cut oxygen generated plasma is forced to swirl as it enters the plasma orifice. Secondary gas is injected downstream of the plasma nozzle (Fig. 1.6.).

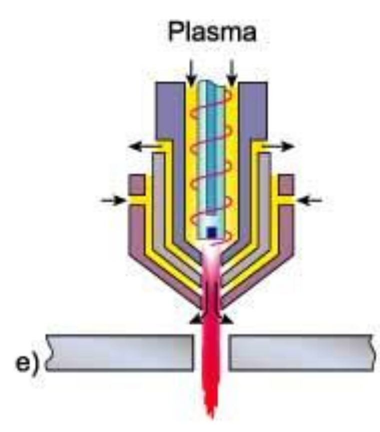

Fig. 1.6. High tolerance plasma [6]

There are some HTPAC systems that have magnetic field surrounding the arc. This magnetic field stabilizes plasma jet because it maintains the rotation created by swirling gas [6; 10].

Advantages:

- cut quality lies between a conventional plasma arc cut and laser beam cut;
- narrow kerf width;
- less distortion due to smaller heat affected zone.

Main disadvantage – maximum thickness is up to 20mm and cutting speed is lower than conventional plasma and 60 to 80% lower than speed of laser cutting [6; 10].

1.4. Effect of PAC on mild steel

By using PAC method most of heat energy generated by electric arc and chemical reactions is used to melt metal in cutting zone. However, some heat conducts away from kerf and heats metal near it. In fact, during PAC gas or water is used to isolate cutting area from surrounding atmosphere, kerf is cooled down. Metal heating and cooling cause chemical and microstructural changes in the metal near the cut edge. Area which is effected by this thermal cycle called heat-affected zone (HAZ) (Fig. 1.7.) [12, 13].

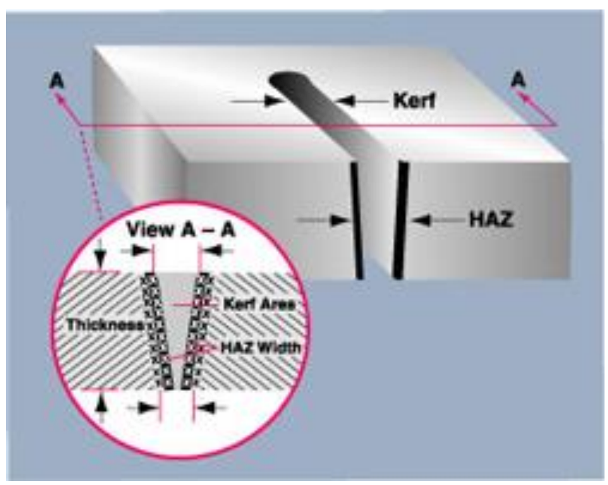

Fig. 1.7. Heat affected zone [14]

At the first look, heat affected zone width is related with thickness of the cut plate. The width of HAZ increases while increasing thickness of plate (Fig. 1.8.). However, to cut various thickness plate, current of arc and cutting speed have to be changed to ensure a good quality of cut, these parameters depends on plate thickness. Also, there are limitations such as highest cutting machine speed for specific contouring [12].

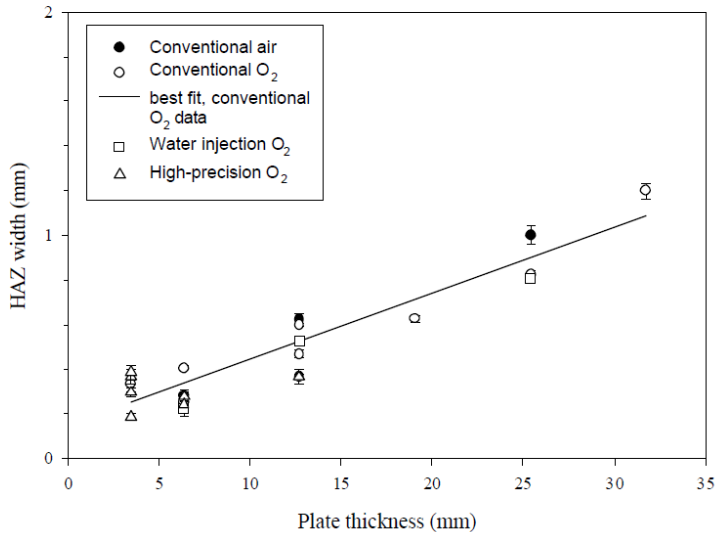

Fig. 1.8. Relation between HAZ and plate thickness [12]

Bainite or bainite with ferrite is usually microstructure of plasma cut edge. Bainite is a hard composite of ferrite and iron carbide. This is a result of rapid thermal cycle where steel is heated and cooled in short time [12].

1.5. Water jet cutting

Water jet cutting is a process which allows to cut very thick material with very high precision, so parts can be cut with a very high tolerance, also this cutting method is very versatile and allows to cut ferrous and nonferrous materials such as stone, rubber, wood and etc. However, this is very slow and expensive method comparing with flame cutting, plasma arc cutting or laser cutting. High-pressure method is used where water is sprayed through a small hole. The hole usually called “orifice” or “jewel”. High pressure and thin water jet allow to concentrate extreme amount of energy into a small area and material is removed from cutting area [15-17].

Various cut quality can be achieved by selecting different cutting parameters. Also, cost of cutting depends on required quality. An extra fine cut can be five times more expensive than rough cut (Fig. 1.9.) [18].

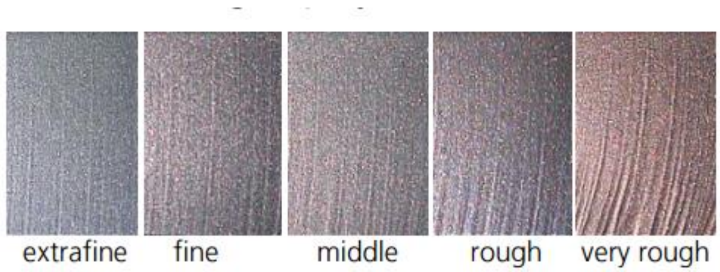

Fig. 1.9. Quality of the cut [18]

There is two types of water jet cutting:

- pure water jet;
- abrasive water jet.

Pure water jet cutting. Pure water jets (Fig. 1.10.) do not have any abrasive elements and material is cut by using only high pressured water. Therefore, this type of water jet can be used in food industry because the material is not contaminated. The main disadvantage is that it can cut only soft material like candy bars, wood, leather and etc. [16].

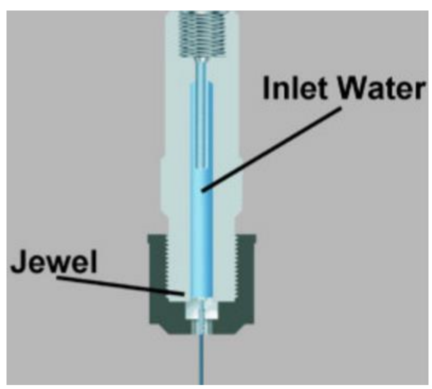

Fig. 1.10. Typical design of a pure water jet nozzle [16]

Pressure of inlet water is from 1300 to 6200 bar. It is forced through a very tiny hole in the jewel, where hole diameter is 0.18-0.4 mm. High pressure and tiny jewel hole creates very thin beam of water, and water injection speed is close to the speed of sound (about 960 km/hour) [16].

Abrasive water jet cutting. This type of water jet cutting is performed in a similar principle as pure water jet for water beam creation. The main difference is that there are some abrasive particles added into the stream and mixed (Fig 1.11.). The high velocity water creates a vacuum which pulls abrasive from abrasive supply line. These abrasive particles mixes with water in the mixing tube. Water jet beam accelerates abrasive particles and they become fast enough to cut hard materials such steel, stone and etc. Accelerated abrasive and water creates the force which is capable enough to erode the material [13; 18].

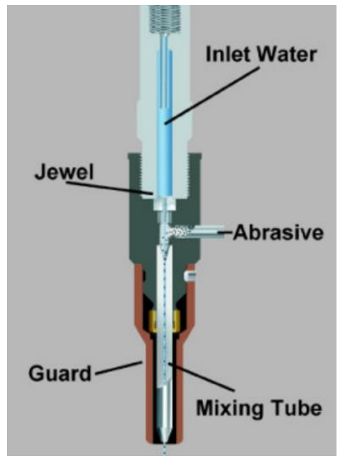

Fig. 1.11. Typical design of abrasive water jet nozzle [16]

1.6. Laser cutting

It is another one sheet metal cutting process. Laser beam is created by laser source called resonator. Mirrors or transport fiber can be used for laser beam conduction to cutting head. In the cutting head there is a lens which focuses laser beam at a very high power and very small diameter. By using focused laser beam the material is heated, melted and some of it is vaporized. By using flow of cutting gases from the cutting head melted metal is removed from kerf. The cut can be produced by moving a work piece or by moving cutting head. Typical laser cutting process is shown in Fig 1.12. [19; 20].

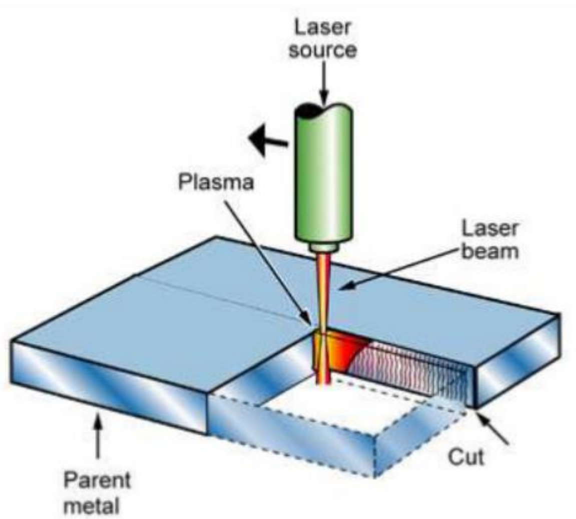

Fig. 1.12. Laser cutting [19]

In metal working industry, there are two the most common types of laser:

- CO2 laser
- fiber laser

CO2 laser. Carbon dioxide laser or in other words CO2 laser beam (Fig 1.13.) is generated in mixture of gases. This mixture generally consists of carbon dioxide, helium and nitrogen. This type of laser usually emits waves which length is approximately 10.6μm. This type of laser is electronically pumped by using electric discharge [19-21].

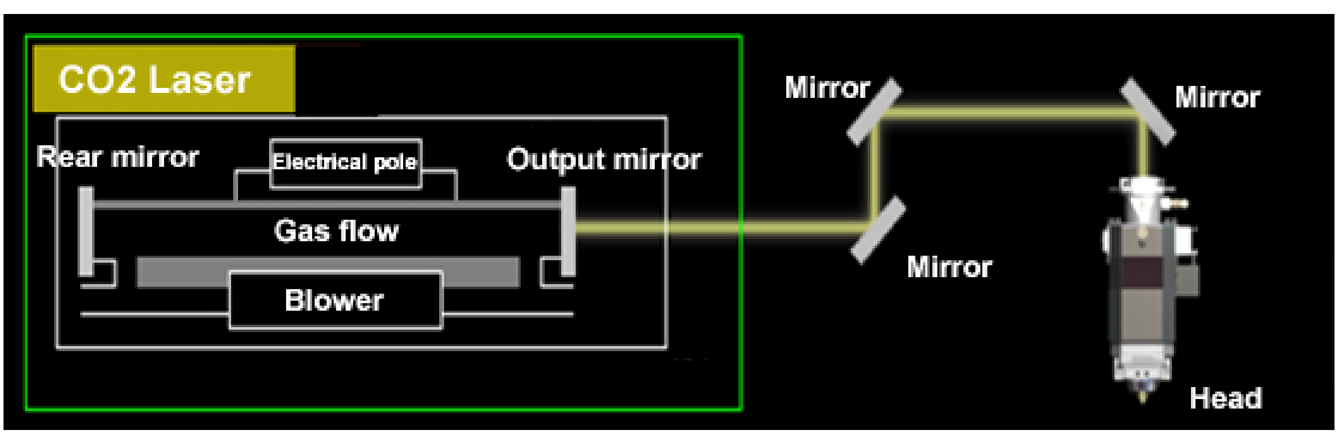

Fig. 1.13. CO_2 laser cutting [11]

Fiber laser. This type of laser belongs to family of lasers called solid state lasers. Fiber lasers (Fig 1.14.), disk lasers and Nd:YAG lasers belong to this group of lasers. The beam of fiber laser is created by series of diodes and transmitted through an optical fiber where it gets amplified. The amplified laser beam is collimated when it exiting optical fiber and then focused by lens to cut [19-21].

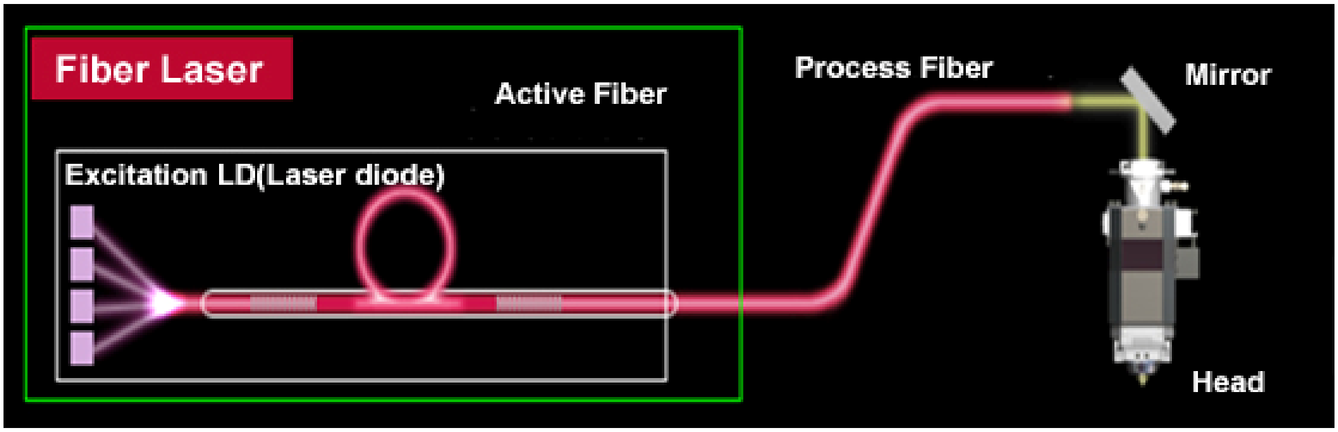

Fig. 1.14. Fiber laser cutting [21]

1.7. Comparison between plasma arc, water jet and laser beam cutting methods

Each of different cutting methods have their own advantages and disadvantages comparing with other method. Comparison of sheet metal cutting processes is given bellow in table 1.1.:

Table 1.1. Comparison of methods [22-24]

Method of cutting	Plasma	Abrasive water jet	Laser
Speed	Fast	Slow	Fast
Material thickness	Medium and thick	Thick and thin	Thin and medium
Size of details	Large	Small and large	Small and large
Shape	Simple	Complicated	Complicated
Material suitable for intersection	Metals and conductive materials	Most of solid	Homogeneous with no reflective bodies
Materials covered with rust	Average	Very good	Good
Composites	No	Yes	No
Material hardening	Yes	No	Yes
Thermal deformation	Yes, wider area	Lack	Yes, small area
Hazardous vapors	Yes	No	Yes
Multilayer cutting	Impossible	Possible	Impossible
Precision cutting	Good	High	Higher
Burr formation	Yes	Minimal	Yes
Operating cost	Low	High	Lower

2. RESEARCH PART

Plasma arc cutting effects steel structure because of heat created by cutting process. This heat creates heat affected zone which has different micro structure from main material and it leads to material hardening. By changing cutting parameters, such as cutting speed and cutting amperage, different width of HAZ and different surface hardness near the kerf can be achieved.

Main goals for this research is to analyze relations between cutting parameters and features of heat affected zone. The research has different steps which are described in the following subchapters.

2.1. Preparation of blanks

Plasma arc cutting machine “Micro Step PLS 6001.25Pr” is used for preparation of material (Fig. 2.1.). Main technical parameters of this machine are given in table 2.1.

Fig. 2.1. Plasma arc cutting machine PLS 6001.25 Pr

Table 2.1. Technical parameters of plasma cutting machine [25]

Working length	6000 mm
Working width	2500 mm
Number of cutting heads	1
Max. thickness of material cut by plasma	50 mm
Positioning speed in X direction	40 m/min
Positioning speed in XY	56 m/min
Positioning accuracy	± 0.06 mm

Three different steel sheets are used as material:

- S235JR+N T=5 mm
- S235JR T=15 mm
- AISI 316L T=6 mm

Chemical composition of steel S235JR is given in table 2.2. and chemical composition of steel AISI 316L is given in table 2.3.

Table 2.2. Chemical composition of steel S235JR [26]

C max. %	**Mn max. %**	**Si max. %**	**P max. %**	**S max. %**	**N max. %**	**Cu max. %**	**Other max. %**
0.17	1.4	-	0.04	0.04	0.012	0.55	0.5

Table 2.3. Chemical composition of steel AISI 316L [27]

C max. %	**Mn max. %**	**Si max. %**	**P max. %**	**S max. %**	**Ni max. %**	**Cr max. %**	**Other max. %**
0.03	2.0	0.75	0.045	0.03	10-14	16-18	0.01

There were 18 pieces of blanks cut for research by changing cutting speed and cutting amperage and material. 7 pieces of them were made of steel S235JR+N T=5 mm, and other 7 pieces - of steel S235JR T=15 mm and 4 pieces of AISI 316L. General dimension of each peace was 100 mm in length and 100 mm in width. Also, each blank had 45 mm length cut inside of it. Sketch of the blanks is shown in Fig. 2.2.:

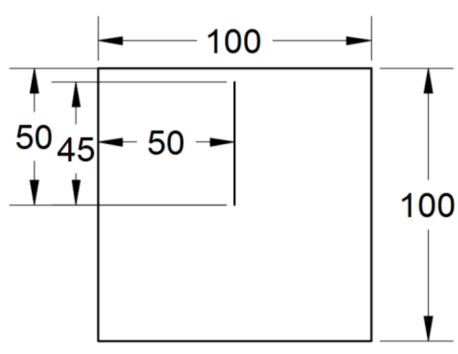

Fig. 2.2. Sketch of the blank

The following table (table 2.4.) contains information about marking numbers of blanks and cutting parameters. Figure 2.3. shows cutting parameters during cutting process:

Table 2.4. Cutting parameters of blanks

No.	Steel grade	Thickness of sheet, mm	Cutting speed, mm/min	Amperage, amperes	Voltage, volts
1	S235JR	15	1050	90	140
2	S235JR	15	840	90	140
3	S235JR	15	700	90	140
4	S235JR	15	560	90	140
5	S235JR	15	420	90	140
6	S235JR	15	1050	160	124
7	S235JR	15	1050	200	150
8	S235JR+N	5	1050	90	133
9	S235JR+N	5	850	90	133
10	S235JR+N	5	650	90	133
11	S235JR+N	5	450	90	133
12	S235JR+N	5	1250	90	133
13	S235JR+N	5	1050	60	128
14	S235JR+N	5	1050	35	119
15	AISI 316L	6	1320	75	149
16	AISI 316L	6	1000	75	149
17	AISI 316L	6	700	75	149
18	AISI 316L	6	400	75	149

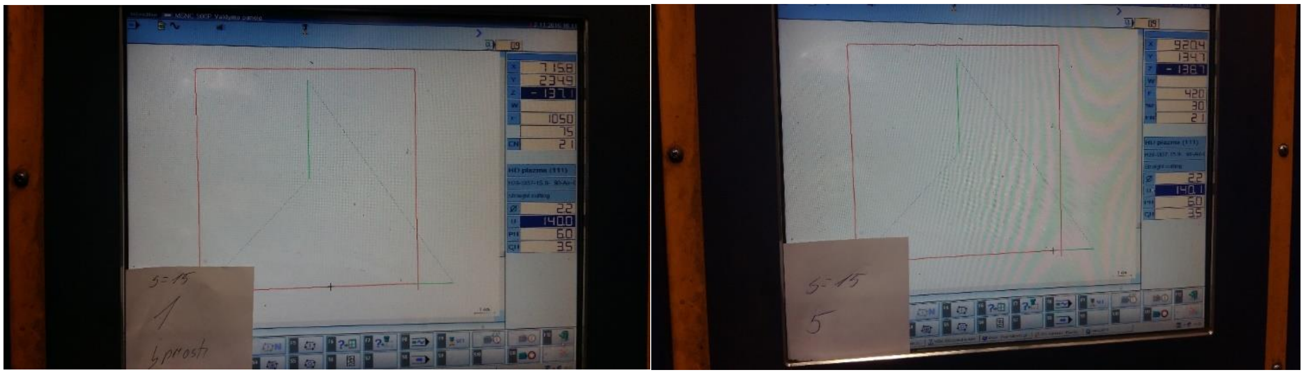

Fig. 2.3. Cutting parameters during cutting

After blanks were cut by plasma, they need to be cut into work pieces for measurements and research. For this operation, a band saw and cooling liquid were used. Cooling is very important in this stage because there should be no additional heat source to achieve accurate results. The sketch for blank cutting is shown in Fig. 2.4.:

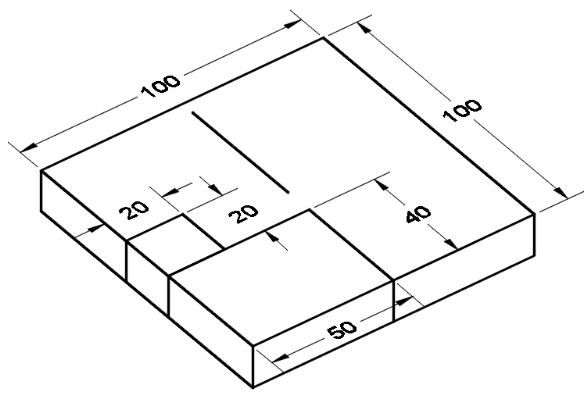

Fig. 2.4. Sketch of work pieces

2.2. Preparation of work pieces for research

When the work pieces are cut out of blanks they need to be prepared for measurements and researches. Because of unrelated methods of research, there are two different ways to prepare work pieces.

2.2.1. Preparation of work pieces for hardness and surface roughness measurements

A work piece of 40x50 mm is chosen for hardness and roughness measurements. Hardness can be measured on flat and polished surface only. For surface treatment the right surface needs to be chosen because it is necessary to measure how the hardness changes going deep into the metal from the surface which is cut by plasma arc. For roughness measurement additional surface treatment is not required, but treatment does not have any negative results. In the following sketch it is shown which one of the surfaces is selected for surface treatment (Fig. 2.5.):

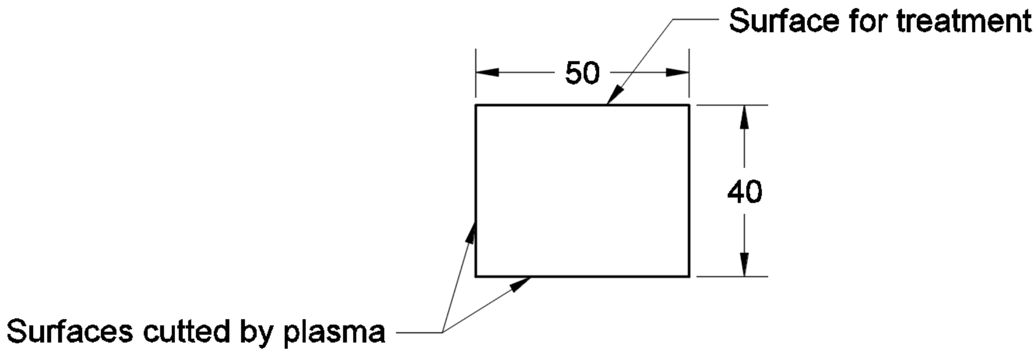

Fig. 2.5. Surface for treatment

When the right surface is selected it needs to be grinded, because it is not flat after band saw cutting, has some strips on it and cannot be used for measurements. Therefore, different roughness sand paper is used. Every work piece was grinded manually in several steps. Starting with sand papers which has roughness P80 then P280, P600, P1000, P1200, P1500, P2000 and finishing with sand paper P2500. Surfaces before and after grinding is shown in Fig. 2.6. and Fig. 2.7.

Fig. 2.6. Surface before grinding

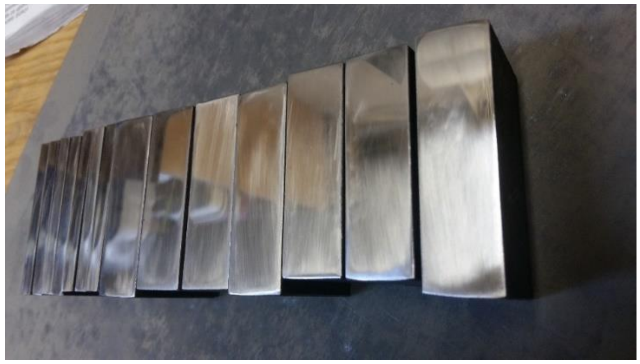

Fig. 2.7. Surface after grinding

2.2.2. Preparation of work pieces for HAZ measurements

For measurement of width of the heat affected zone surface of work piece that needs to be polished, pieces of 20x20 were chosen. Because the work piece is too small to be fixed in polishing machine, it needs to be placed into plastic tube and poured over by polyester resin (Fig. 2.8. and Fig. 2.9.). This has several steps:

- cut plastic tube Ø32x1.5 mm into pieces 20 mm in length;
- seal one end of tube with adhesive tape;
- place work piece in it;
- mix polyester resin with hardener;
- pour polyester resin into sealed tube to fix work piece.

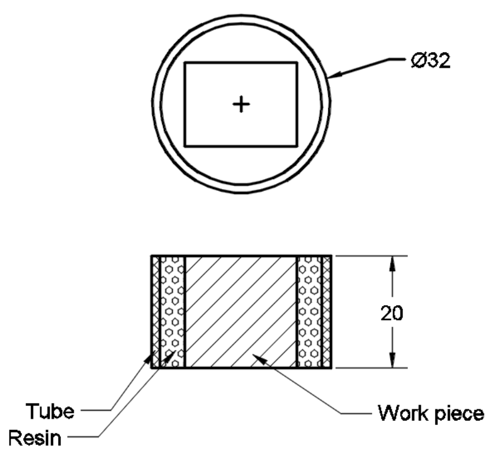

Fig. 2.8. Sketch of fixed work piece

Fig. 2.9. Work pieces fixed into resin

When the resin hardens, one end of the work piece needs to be trimmed slightly by using lathe, just to create flat surface (Fig. 2.10.). It helps to polish work much easier because less of material needs to be removed during the polishing.

Fig. 2.10. Work pieces after turning

Trimmed work piece now can be polished to create smooth and shiny surface. Polishing machine SMARTLAM® 2.0. was used for polishing (Fig. 2.11. and table 2.5.) .

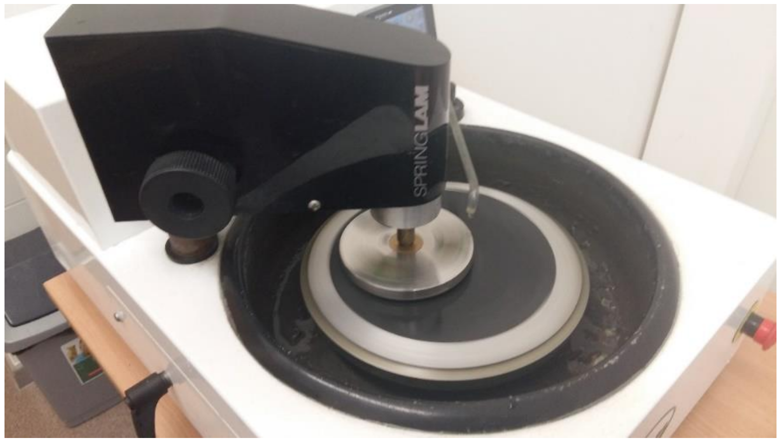

Fig. 2.11. Polishing machine SMARTLAM® 2.0

Table 2.5. Technical parameters of polishing machine [28]

Plate capacity	Ø 200 - Ø 300 mm
Body	Steel, coated with epoxy paint
Bowl	Removable resin basin for easy cleaning
Controls	3.5” colour touch screen to control the machine: start/stop, timer, speed and direction of plate, water solenoid valve
Plate rotating speed	Variable, from 20 to 650 rpm
Rotation	Clockwise / counter clockwise
Programming	Load 9 programms
Export	USB connection
Water inlet	Removable pipe, with flow rate adjustment and safety solenoid valve
Power max	0.75 kW
Voltage	230 V – 50 Hz single-phase
Dimensions L x H x D	450 x 300 x 650 mm
Mass	30 kg

Polishing cannot be performed without abrasive liquid and Lam Plan abrasive suspension NEODIA 1M was used for that purpose (Fig. 2.12.).

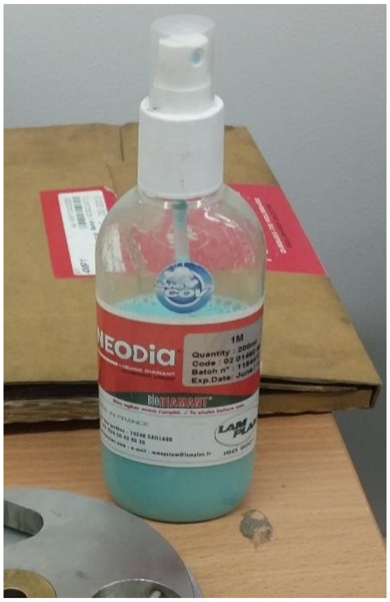

Fig. 2.12**.** Abrasive suspension NEODIA 1M

After polishing, surfaces of work pieces become flat and shiny, without any scratches (Fig. 2.13.).

Fig. 2.13. Work pieces after surface polishing

When work pieces are polished they are ready for further researches.

2.3. Researches

2.3.1. Hardness investigation

Due to the fact, material after plasma arc cutting near the cut kerf becomes much harder than main material. To investigate hardness changes, a hardness testing instrument INOVATEST VERZUS 750CCD is used (Fig 2.14.). Some information about the instrument:

The VERZUS 750 series are a new generation of hardness testing instruments. The testers are constructed around a rock solid C-frame with unparalleled rigidity. The closed loop system based on a load cell and precision force actuator guarantees the best GR & R results ever seen on Rockwell hardness testers. The tester meets or exceeds the ISO, ASTM and JIS standards and conforms to Nadcap auditing. Test forces range from 1kgf/9.8N to 250kgf/2.45kN, Advanced algorithms, digital filter technology and state of the art electronics provide unmatched force control. The test cycle can be as little as 13 seconds (at a dwell time of 10 seconds). Depth measurement via an optical system with a direct reading of 0.1 micron. VERZUS stands for versatile. The 750CCD is equipped with Rockwell, Superficial Rockwell, Vickers, Brinell, HVT, HBT and Depth ball measurement. All models also include Plastic testing scales according to ISO 2039/1. [29]

Fig. 2.14. Hardness testing instrument Inovatest Verzus 750ccd

Several steps should be done for hardness measurement:

- work piece 40x50 mm placed on the measuring table and fixed by using special grease;
- table needs to be raised or lowered until a focused view of work piece surface appears;
- work piece needs to be moved until plasma cut side appears through the display;
- table with the work piece to be moved gently to the position to apply load;
- button to apply load needs to pushed and the machine starts to apply load in the work piece and then diamond prism goes into material and then automatically goes out;
- then worktable gently moved to the position for measurements;
- a rectangular mark is visible on the display (Fig. 2.15.):

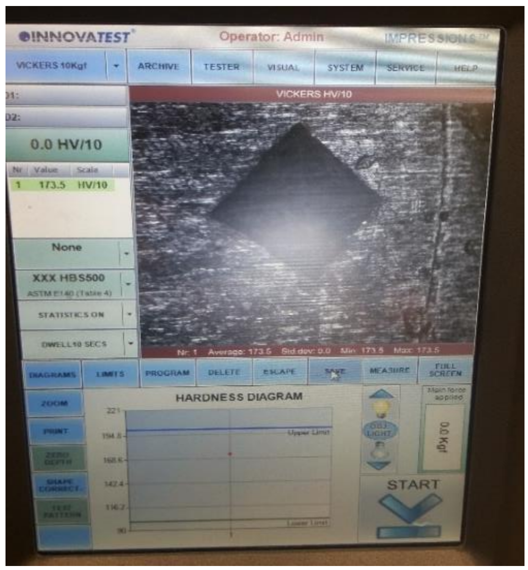

Fig. 2.15. View of rectangular mark

- size of the mark needs to be measured. Most of the time the machine detects edges of the mark automatically which allows to measure size of it very quickly. Although, sometime the machine detects edges incorrectly and the measurements need to be done manually by using lines on the display (Fig. 2.16.):

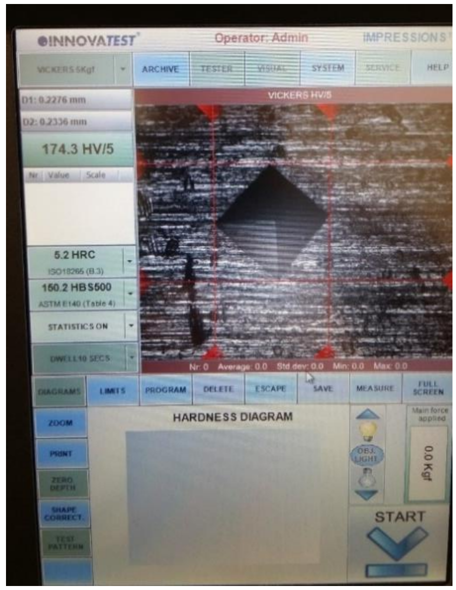

Fig 2.16. Display during measurements

- if the results of the measurement are accepted, they go into hardness diagram as a part of it.

The steps listed above are for one measurement only. To analyze changes of hardness, several measurements need to be done until the hardness decreases to hardness of main material. Measuring table changes position automatically at 0.7 mm with every new measurement. Illustration how measurement was done is shown in Figure 2.17.:

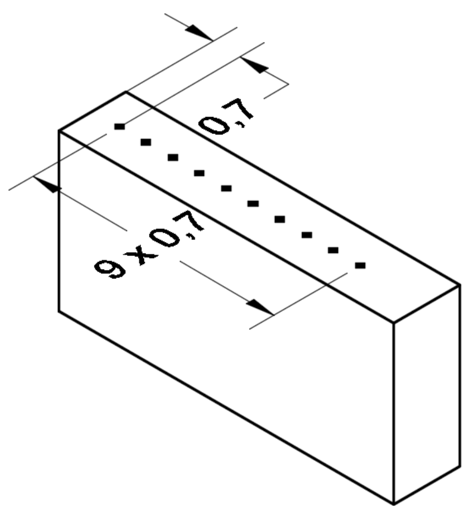

Fig. 2.17. Measuring points

After several measurements hardness diagram is completed and it looks like in Figure 2.18.:

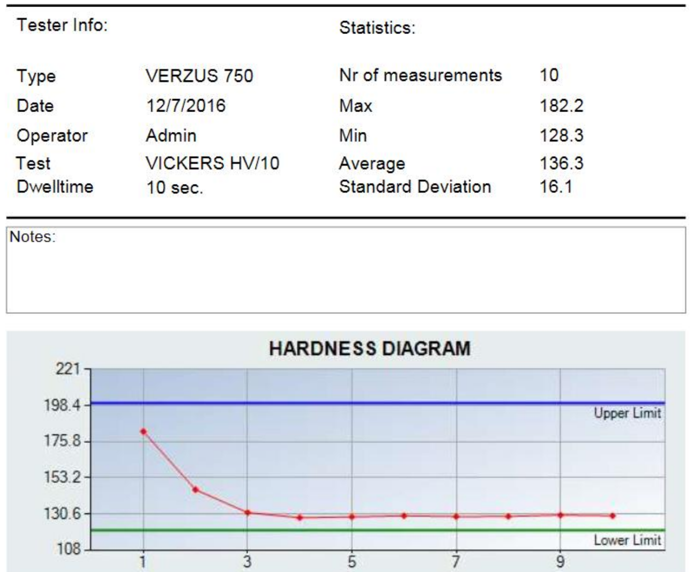

Fig. 2.18. Hardness diagram

2.3.2 Heat affected zone investigation

For this part of research, a polished work piece and a microscope with scale binocular was needed. In that case microscope ZEISS Scope A1 was used (Fig. 2.19.).

Fig. 2.19. Microscope ZEISS Scope A1

Every work piece needs to be coated with reagent before placing it under microscope lens. Reagent makes structure changes much more visible so it helps to see what width is HAZ. When one work piece is placed under microscope lens, the view is focused manually and measured by using scale on binocular. Also, there are a few photos taken of each work piece. The examples of the views are shown in Figure 2.20.:

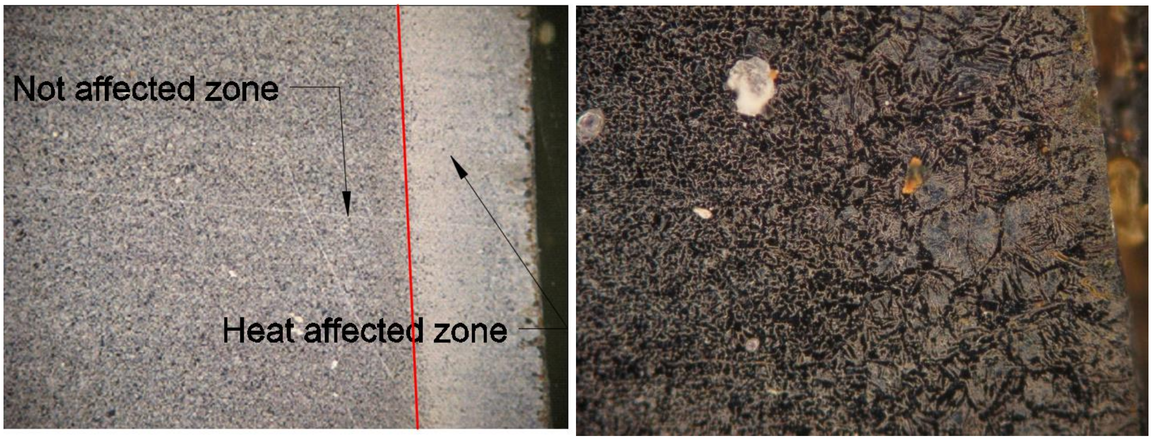

Fig. 2.20. Examples of heat affected zone

2.3.3 Surface roughness investigation

To investigate roughness of surfaces after plasma arc cutting surface roughness tester TR220 was used (Fig. 2.21.). Main specifications of this device is listed in table 2.6.:

Table 2.6. Main specifications of roughness tester TR220 [30]

Roughness	Ra, Rq, Rz, Rt, Rp, Rv, Ry, RS, RSm, RSk, Rz (JIS), R3z, Rmax, RPc, Rk, Rpk, Rvk, Mr1 und Mr2;
Measuring range	Ra: 0.005 - 16 μm ; Rz: 0.02 - 160 μm
Resolution	0,001 μm
Cross wavelength (cut-off)	0.25 mm / 0.8 mm / 2.5 mm / Auto
Traversing length Ln	1 - 5 cut-off (selectable)

Fig. 2.21. Surface roughness tester TR220

During the measurements of surface roughness, no movement of tester or work piece is allowed. Because of this, measurements were done by using measuring table (Fig. 2.22.) which ensures stability of the tester and stability of work piece.

Fig. 2.22. Measuring table

Roughness measurements were done on three different levels on work pieces of 15 mm thick to investigate if the roughness of surface is different on the same work piece. 5 mm and 6 mm work pieces was measured once, at middle measurement line. The measurements lines are illustrated below in Figure 2.23.:

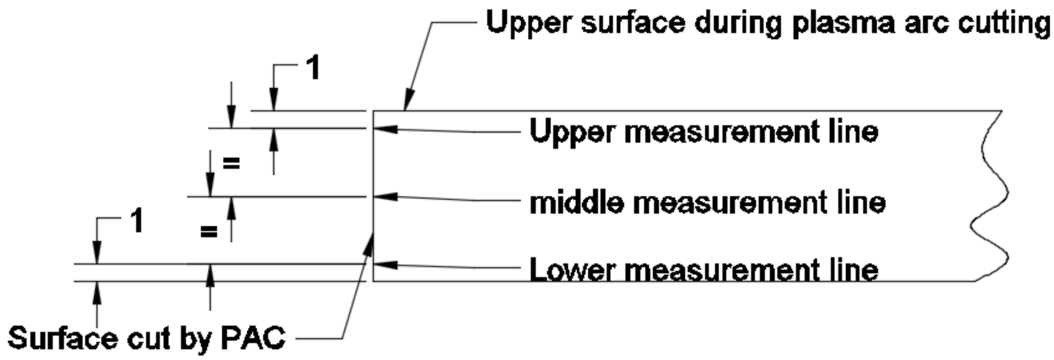

Fig. 2.23. Roughness measurement lines

For roughness investigation, three main parameters was chosen to measure:

- Ra- Arithmetic Average Roughness
- Rq- Geometric Average Roughness
- Rz- Mean Roughness depth

3. RESULTS AND DISCUSSIONS

This chapter shows results that reveal how plasma arc cutting parameters affects hardness of heat affected zone, width of the heat affected zone and cut surface roughness. To analyze data, Microsoft Excel program was used. In the table below, there are the results of all the measurements which were done.

3.1. Results of hardness measurements

As described in previous chapter, different PAC parameters such as cutting speed and amperage were used for cutting blanks for work pieces. Following results reveals how hardness at distance of 0.7mm from cut edge is affected by cutting parameters and how hardness is changing in measuring it from cut edge to deeper material.

Relation between cutting speed and hardness near cut edge on 15mm thickness plates

Table 3.1. Hardness of 15mm thick work pieces cut in different cutting speeds

Plate No.	Cutting speed, mm/min	Amperage, A	Hardness, HV/10
1	1050	90	173.55
2	840	90	185.96
3	700	90	159.37
4	560	90	164.94
5	420	90	195.52

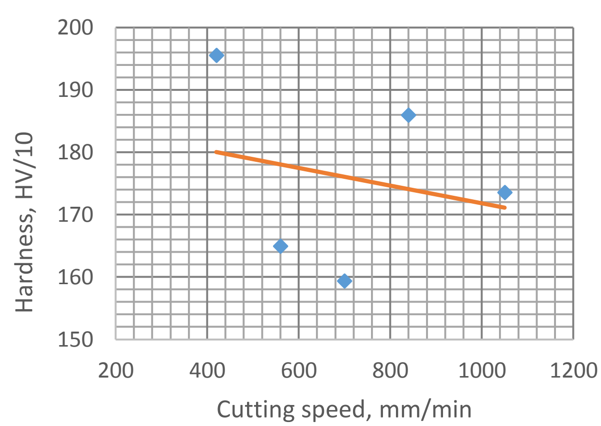

Fig. 3.1. Hardness of 15mm thick work pieces cut in different cutting speeds

Relation between cutting speed and hardness near cut edge on 5 mm thickness plates

Table 3.2. Hardness of 5mm thick work pieces cut in different cutting speeds

Plate No.	Cutting speed, mm/min	Amperage, A	Hardness, HV/10
12	1250	90	199.88
8	1050	90	174.34
9	850	90	174.78
10	650	90	173.42
11	450	90	159.27

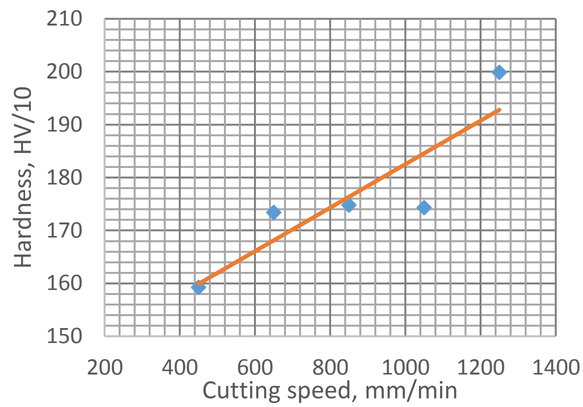

Fig. 3.2. Hardness of 5mm thick work pieces cut in different cutting speeds

Relation between cutting speed and hardness near cut edge on 6 mm thickness plates

Table 3.3. Hardness of 6 mm thick work pieces cut in different cutting speeds

Plate No.	Cutting speed, mm/min	Amperage, A	Hardness, HV/10
15	1320	75	186.31
16	1000	75	195.87
17	700	75	184.66
18	400	75	195.28

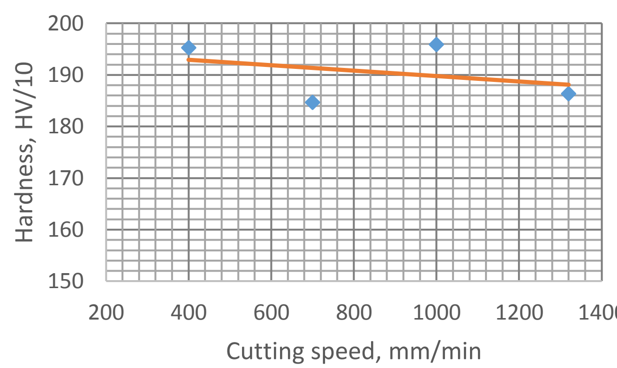

Fig. 3.3. Hardness of 6 mm thick work pieces cut in different cutting speeds

Relation between cutting amperage and hardness near cut edge on 15mm thickness plates

Table 3.4. Hardness of 15 mm thick work pieces cut in different amperages

Plate No.	Cutting speed, mm/min	Amperage, A	Hardness, HV/10
1	1050	90	173.55
6	1050	160	170.57
7	1050	200	187.2

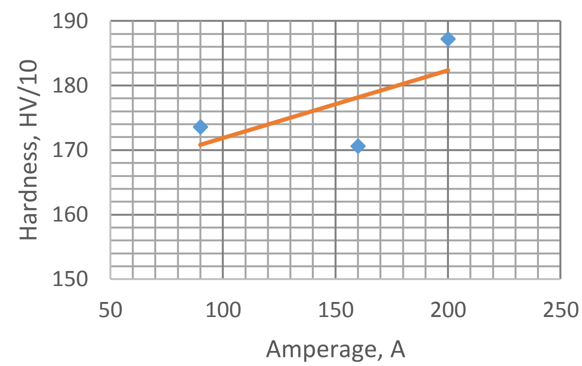

Fig. 3.4. Hardness of 15 mm thick work pieces cut in different amperages

Relation between cutting amperage and hardness near cut edge on 5 mm thickness plates

Table 3.5. Hardness of 5 mm thick work pieces cut in different amperages

Plate No.	Cutting speed, mm/min	Amperage, A	Hardness, HV/10
8	1050	90	174.34
13	1050	60	181.54
14	1050	35	182.21

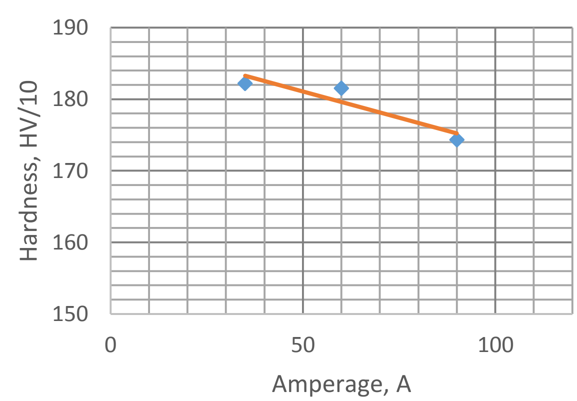

Fig. 3.5. Hardness of 5 mm thick work pieces cut in different amperages

Results of hardness measurements at different distance from cut edge

In this case, series of measurements were done with every work piece. First hardness measurement was done at distance of 0.7 mm from cut edge, second one at 1.4 mm, third one at 2.1mm and so on. The result is revealed at the diagram below:

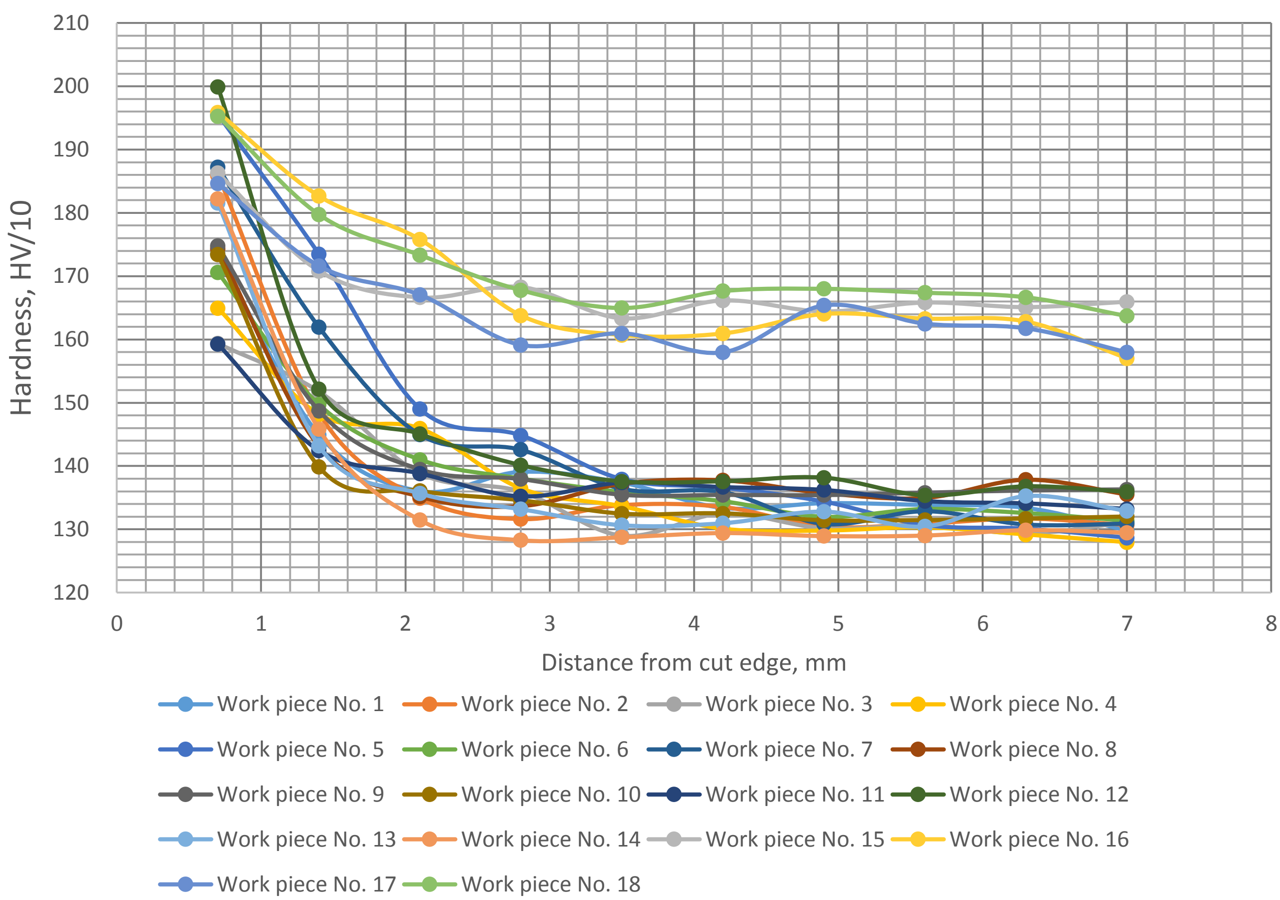

Fig. 3.6. Hardness changes by distance from cut

3.1.1. Review of the result of hardness measurements

The results shows that there is no strong relation between hardness of steel near cut and cutting speed or cutting amperage. In figures 3.1. and 3.3. is it possible to see that when cutting speed is high then hardness of material is reduced, but in figure 3.2. phenomenon have opposite meaning. Figures 3.4. and 3.5. is opposite to each other and do not allow to make proposition that hardness near cut related with cutting parameter. These results can be explained by Y. Wu , C. M. Hackett and S. T. Eickhoff. article: the hardness data taken near the cut edge suffered from scattering of the measurement results because of the variety microstructural features present. For instance, a grain containing predominantly bainite would be relatively hard, while one consisting of more ductile pearlite would be less so. Placement of the micro-hardness indenter in different grains resulted in a range of hardness values [12]. The variety of microstructural feature near cut edge is clearly visible on Figure 3.7.:

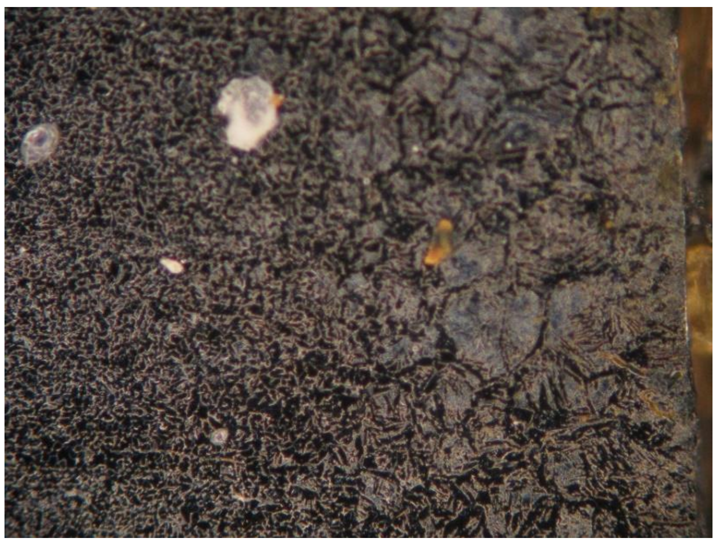

Fig. 3.7. Microstructure near cut edge

However, Figure 3.6. shows strong relation between material hardness and distance from cut edge. The highest hardness is at cut edge and going deeper into material hardness going down until reach hardness of main material. The Figure 3.6. shows that stainless steel AISI 316L, at the distance of 0.7 mm from cut edge, is about 1.15-1.20 times harder than main material. Steel S235JR and Steel S235JR+N, at distance of 0.7 mm from the cut edge, is about 1.3-1.4 times harder than its main material.

3.2. Results of heat affected zone width measurements

Work pieces cut by using various PAC parameters is used for HAZ width measurements. Following subchapters reveal how the width of heat affected zone changes applying different cutting speed and cutting amperage. In this case, only mild steel S235JR t=15 and S235JR+N t=5 is in scope of research.

Relation between cutting speed and HAZ width on 15 mm thickness plates

Table 3.6. HAZ width and cutting speed relation on 15mm thick steel S235JR

Plate No.	Cutting speed, mm/min	Amperage, A	HAZ width, mm
1	1050	90	715
2	840	90	877.5
3	700	90	1593
4	560	90	1625
5	420	90	3380

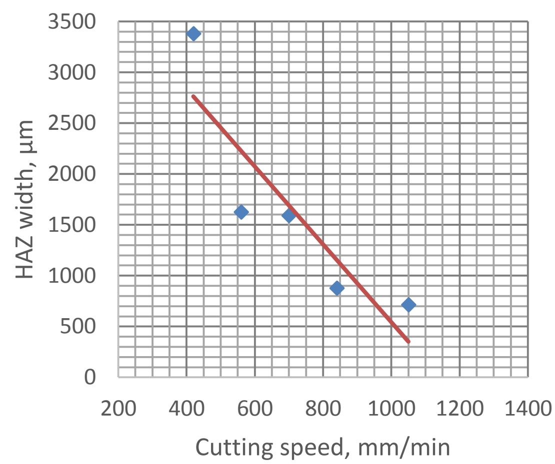

Fig. 3.8. HAZ width and cutting speed relation on 15mm thick steel S235JR

Relation between cutting speed and HAZ width on 5 mm thickness plates

Table 3.7. HAZ width and cutting speed relation on 5 mm thick steel S235JR+N

Plate No.	Cutting speed, mm/min	Amperage, A	HAZ width, mm
12	1250	90	715
8	1050	90	910
9	850	90	1170
10	650	90	1235
11	450	90	1430

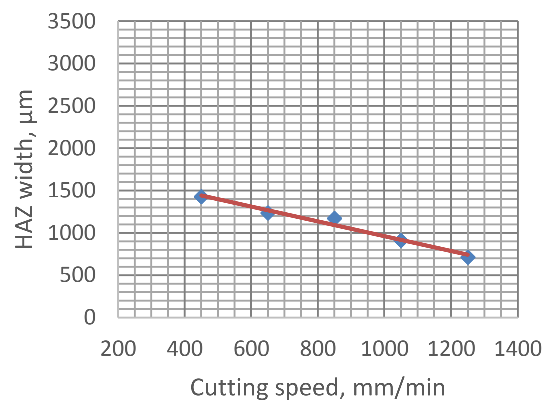

Fig. 3.9. HAZ width and cutting speed relation on 5 mm thick steel S235JR+N

Relation between cutting amperage and HAZ width on 15 mm thickness plates

Table 3.8. HAZ width and cutting amperage relation on 15mm thick steel S235JR

Plate No.	Cutting speed, mm/min	Amperage, A	HAZ width, mm
1	1050	90	715
6	1050	160	780
7	1050	200	1300

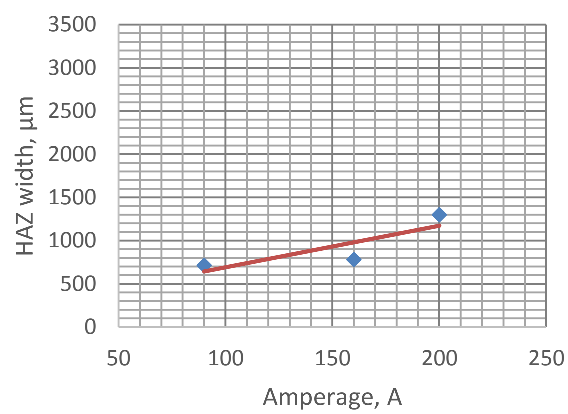

Fig. 3.10. HAZ width and cutting amperage relation on 15mm thick steel S235JR

Relation between cutting amperage and HAZ width on 5 mm thickness plates

Table 3.9. HAZ width and cutting amperage relation on 5 mm thick steel S235JR+N

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**HAZ width, mm**
8	1050	90	910
13	1050	60	878
14	1050	35	650

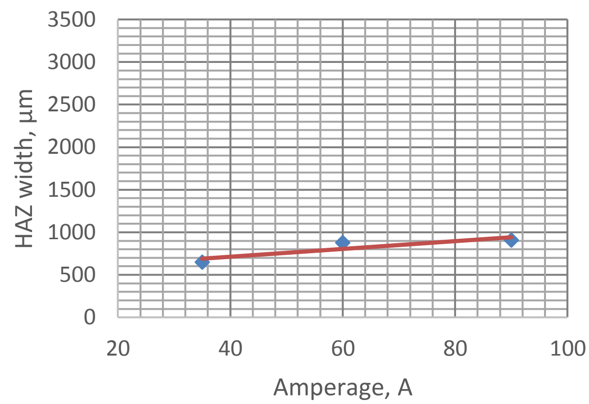

Fig. 3.11. HAZ width and cutting amperage relation on 5 mm thick steel S235JR+N

3.2.1. Review of the result of HAZ width measurements

According to the charts above, there is clear relation between heat affected zone width and cutting parameters such as speed and amperage. The Figures 3.8. and 3.9. reveal that cutting speed has a big impact for width of HAZ. Increased cutting speed creates narrower heat affected zone, and vice versa reduced speed creates wider HAZ. By increasing cutting speed from 420 mm/min to 1050 mm/min on 15 mm thick steel width of the heat affected zone reduces from 3380 µm to 715 µm. Similar results are visible by measuring HAZ of 5 mm thick steel. In this case, increasing cutting speed from 450 mm/min to 1250 mm/min heat affected zone reduces from 1430 µm to 715 µm. This can be explained a way that material being cut in a low speed has much more time to absorb heat created by plasma arc.

The Figures 3.10. and 3.11. shows that cutting amperage has impact on HAZ as well as cutting speed, but in this case meaning is opposite. Increased amperage creates wider heat affected zone and when amperage is reduced HAZ become narrower. Increased amperage from 90 A to 200 A creates wider heat affected zone of 1.82 times on 15 mm thick steel and increased amperage from 35 A to 90 A creates wider heat affected zone of 1.4 times on 5 mm thick steel.

However, there are some kind of limitations on cutting speed and amperage, if cutting speed is increased too much, plasma arc will not penetrate the steel and only partial cut will be made. The same situation is with low amperage: too low amperage does not penetrate the steel as well.

3.3. Results of surface roughness measurements

This subchapter is dedicated to find out relation between plasma arc cutting speed, amperage and surface roughness. For this reason, cut surface is measured by roughness tester. On each 15 mm thick plate there were three measurements done, and only one measurement was performed on 5 mm and 6 mm thick plates. Description of measurements equipment and procedures is presented in chapter 2.3.3.

Relation between cutting speed and surface roughness Ra on 15 mm thickness plates

Table 3.10. Roughness Ra and cutting speed relation on 15mm thick steel S235JR

Plate No.	Cutting speed, mm/min	Amperage, A	Ra Upper line, µm	Ra Middle line, µm	Ra Lower line, µm
1	1050	90	2.025	2.19	3.332
2	840	90	1.277	1.362	1.875
3	700	90	1.036	1.244	2.085
4	560	90	0.936	1.136	3.795
5	420	90	0.889	1.046	4.416

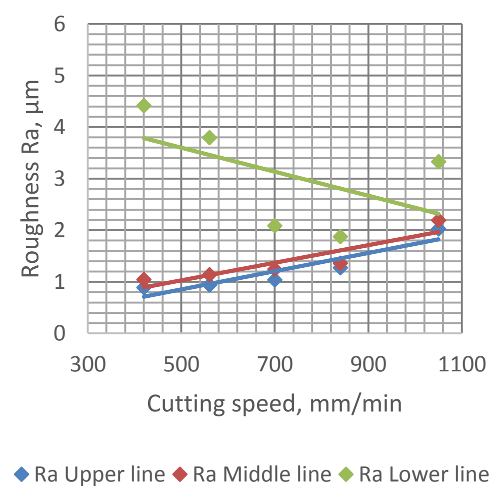

Fig. 3.12. Roughness Ra and cutting speed relation on 15mm thick steel S235JR

Relation between cutting speed and roughness Rq on 15 mm thickness plates

Table 3.11. Roughness Rq and cutting speed relation on 15mm thick steel S235JR

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**Rq Upper line, µm**	**Rq Middle line, µm**	**Rq Lower line, µm**
1	1050	90	2.751	2.779	4.303
2	840	90	1.642	1.64	2.317
3	700	90	1.288	1.484	2.425
4	560	90	1.236	1.324	4.676
5	420	90	1.104	1.281	5.495

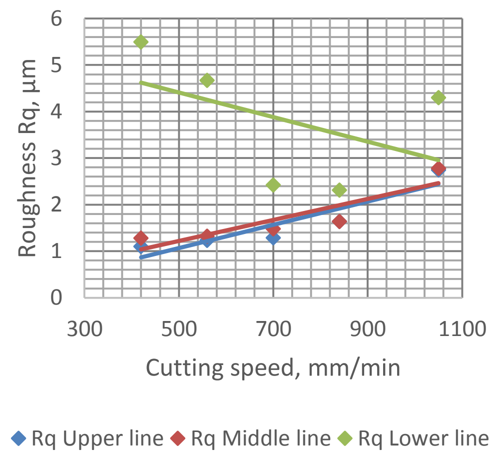

Fig. 3.13. Roughness Rq and cutting speed relation on 15mm thick steel S235JR

Relation between cutting speed and roughness Rz on 15 mm thickness plates

Table 3.12. Roughness Rz and cutting speed relation on 15mm thick steel S235JR

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**Rz Upper line, µm**	**Rz Middle line, µm**	**Rz Lower line, µm**
1	1050	90	6.808	11.79	14.21
2	840	90	7.703	4.855	5.789
3	700	90	4.05	2.722	6.136
4	560	90	5.15	6.91	14.98
5	420	90	4.757	4.253	18.82

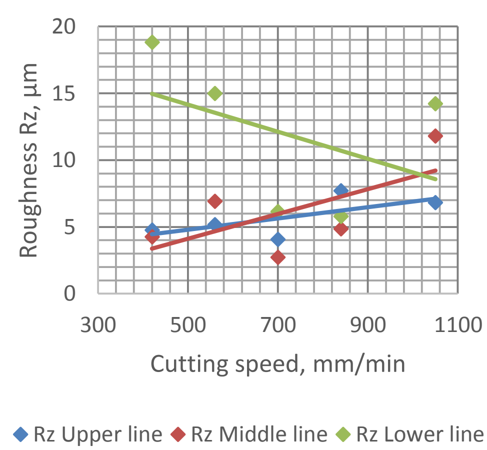

Fig. 3.14. Roughness Rz and cutting speed relation on 15mm thick steel S235JR

Relation between cutting amperage and roughness Ra on 15 mm thickness plates

Table 3.13. Roughness Ra and cutting amperage relation on 15mm thick steel S235JR

Plate No.	Cutting speed, mm/min	Amperage, A	Ra Upper line, µm	Ra Middle line, µm	Ra Lower line, µm
1	1050	90	2.025	2.19	3.332
6	1050	160	1.395	1.656	1.718
7	1050	200	0.66	0.818	1.787

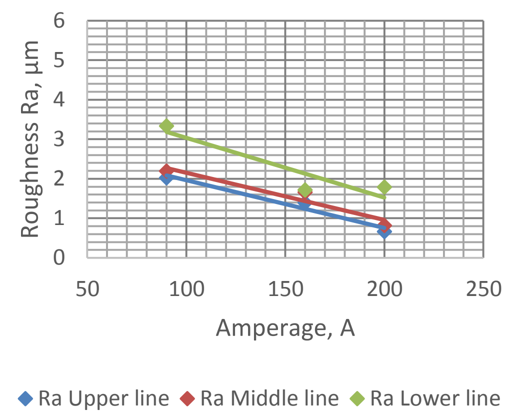

Fig. 3.15. Roughness Ra and cutting amperage relation on 15mm thick steel S235JR

Relation between cutting amperage and roughness Rq on 15 mm thickness plates

Table 3.14. Roughness Rq and cutting amperage relation on 15mm thick steel S235JR

Plate No.	Cutting speed, mm/min	Amperage, A	Rq Upper line, µm	Rq Middle line, µm	Rq Lower line, µm
1	1050	90	2.751	2.779	4.303
6	1050	160	1.879	2.229	2.403
7	1050	200	0.817	1.029	2.66

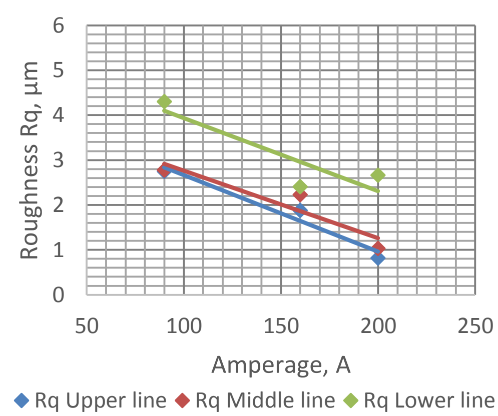

Fig. 3.16. Roughness Rq and cutting amperage relation on 15mm thick steel S235JR

Relation between cutting amperage and roughness Rz on 15 mm thickness plates

Table 3.15. Roughness Rz and cutting amperage relation on 15mm thick steel S235JR

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**Rz Upper line, µm**	**Rz Middle line, µm**	**Rz Lower line, µm**
1	1050	90	6.808	11.79	14.21
6	1050	160	8.542	10.99	10.63
7	1050	200	3.101	4.644	10.46

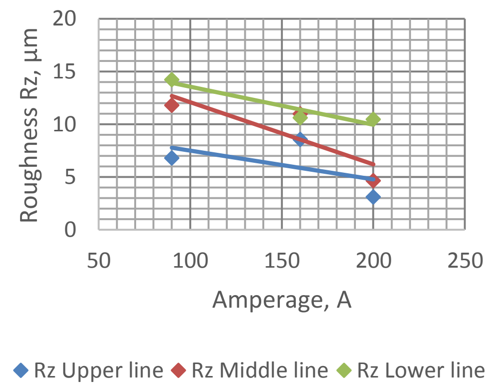

Fig. 3.17. Roughness Rz and cutting amperage relation on 15mm thick steel S235JR

Relation between cutting speed and roughness Ra, Rq and Rz on 5 mm thick plates.

Table 3.16. Roughness Ra,Rq,Rz and cutting speed relation on 5 mm thick steel S235JR+N

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**Ra Middle line, µm**	**Rq Middle line, µm**	**Rz Middle line, µm**
12	1250	90	1.783	2.265	7.101
8	1050	90	1.571	1.962	6.558
9	850	90	1.501	1.786	5.464
10	650	90	1.282	1.624	5.023
11	450	90	1.112	1.436	4.326

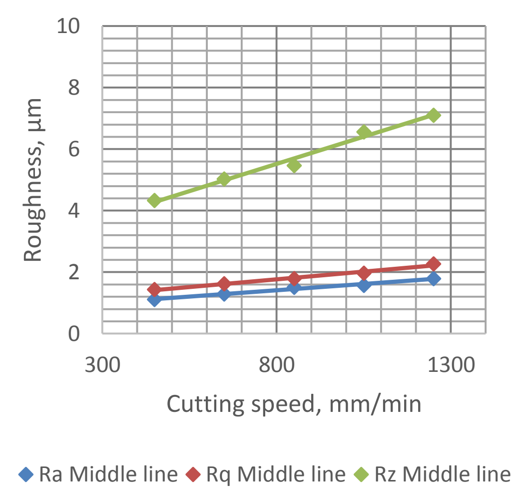

Fig. 3.18. Roughness Ra,Rq,Rz and cutting speed relation on 5 mm thick steel S235JR+N

Relation between cutting amperage and roughness Ra, Rq and Rz on 5 mm thickness plates

Table 3.17. Roughness Ra,Rq,Rz and Amperage relation on 5 mm thick steel S235JR+N

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**Ra Middle line, µm**	**Rq Middle line, µm**	**Rz Middle line, µm**
8	1050	90	1.571	1.962	6.558
13	1050	60	2.123	2.463	7.254
14	1050	35	2.435	2.786	7.698

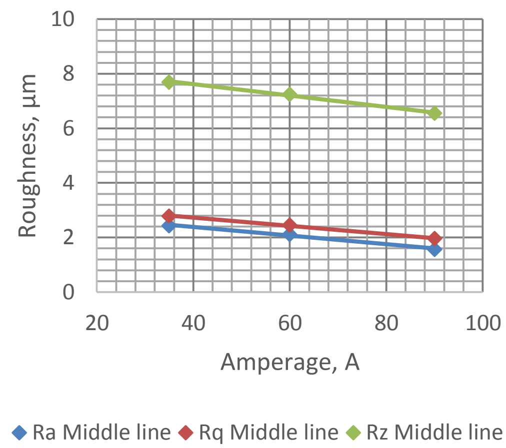

Fig. 3.19. Roughness Ra,Rq,Rz and Amperage relation on 5 mm thick steel S235JR+N

Relation between cutting speed and roughness Ra, Rq and Rz on 6 mm thickness plates

Table 3.18. Roughness Ra,Rq,Rz and cutting speed relation on 6 mm thick steel AISI316L

Plate No.	**Cutting speed, mm/min**	**Amperage, A**	**Ra Middle line, µm**	**Rq Middle line, µm**	**Rz Middle line, µm**
15	1320	75	1.236	1.508	4.573
16	1000	75	1.345	1.713	6.21
17	700	75	1.544	1.863	3.265
18	400	75	1.372	1.745	5.97

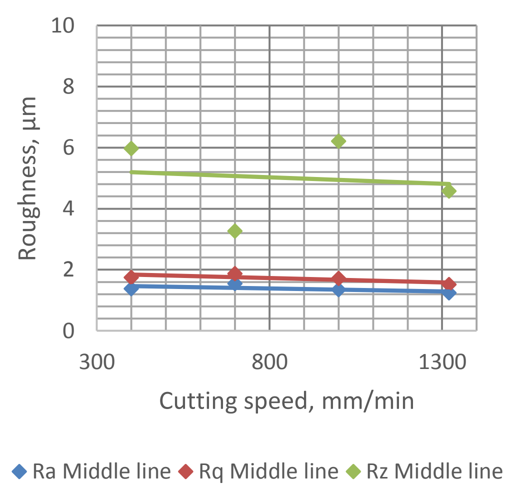

Fig. 3.20. Roughness Ra,Rq,Rz and cutting speed relation on 6 mm thick steel AISI316L

3.3.1. Review of the results of cut surface roughness measurements

The results of cut surface roughness measurements reveal relations between cutting speed, cutting amperage and surface roughness. As it shown in Figures 3.12.-3.14. lower cutting speed positively affects roughness parameter Ra, Rq and Rz in upper and middle parts of the cut by cutting 15 mm thick steel S235JR. The result of lower part roughness measurement shows that reduced cutting speed has opposite meaning and surface becomes rougher. In fact, the result of lower part measurement is quite scattered, so is not possible to state that results are correct. That means, more measurements and researches should be done to state that lower cutting speed creates negative affect on roughness of the lower part of cut. Figures 3.15.-3.17. shows that cuts which were made in higher amperage have smoother surface than cuts made in lower amperage. All three roughness parameters Ra, Rq and Rz confirm this statement.

Results of roughness measurements of the cut of 5 mm thick steel S235JR+N plate show similar results as measurements of 15 mm thick plate. Relation between cutting speed and roughness is shown in figure 3.18. The Figure shows that lower cutting speed leads to smoother surface and vice versa, higher cutting speed leads to rougher surface. In this case roughness was measured only on middle part of cuts and all the results shows the same tendency. Amperage changes lead to similar results as it was with 15 mm thick steel. Lower amperage leads to rougher surface and higher amperage leads to smoother surface, it can be seen in Figure 3.19.

Measurements of plates which were cut by plasma arc cutting of steel AISI316L reveal quite different results that show measurements of carbon steel plates. In this case, the results in Figure 3.20. show that lower cutting speed results higher roughness, it can be confirmed by parameters Ra, Rq and Rz. In fact, the work pieces of steel AISI316L were cut only by changing cutting, so it is not possible to evaluate relation between cutting amperage and surfaces roughness of cuts.

CONCLUSIONS

In this study, variety of measurements were done seeking to discover the impact for cut quality by changing plasma arc cutting parameters such as cutting speed and cutting amperage. As a material for research, steel S235JR t=15, S235JR+N t=4 and steel AISI 316L was chosen. Three different methods were applied to reveal PAC parameter influence on cut quality: hardness measurements near the cut by using hardness testing instrument, HAZ width measurements by preparing metallographic samples and investigating them by using microscope and surface roughness investigation of cuts by using roughness tester. Series of results allow to state the following conclusions:

1. PAC makes material near cut harder than its core material. At distance 0.7 mm from the cut steel S235JR and S235JR+N become about 1.3-1.4 times harder than its core material. Stainless steel AISI 316L become about 1,15-1.18 times harder than its core material at distance 0.7 mm from cut.

2. Hardness of all three grades of material decreases when distance from cut increases until hardness become the same as it is core material.

3. Width of heat affected zone, which is created by plasma arc cutting, can be reduced by increasing cutting speed, and width of heat affect zone can be increased by lowering cutting speed. On 15 mm thick steel S235JR cutting speed increase from 420 mm/min to 1050 mm/min lead to narrower HAZ, it changes from 3380 µm to 715 µm. On 5 mm thick steel S235JR speed increase from 450 mm/min to 1250 leads to HAZ reduction from 1430 µm to 715 µm.

4. Width of HAZ can be reduced by lowering cutting amperage and width of HAZ can be increased by increasing cutting amperage. Amperage change from 90 A to 200 A creates 1.82 times wider heat affected zone on 15 mm thick steel S235JR and increased amperage from 35 A to 90 A creates 1,4 times wider heat affected zone on 5 mm thick steel S235JR+N.

5. Low cutting speed creates smoother cut surface than high cutting speed on mild steel. On stainless steel such as AISI316L low cutting speed creates rougher cut surface than high speed, but this roughness change are very slight.

6. Cut surface roughness on mild steel can be reduced by increasing cutting amperage and roughness can be increased by lower cutting amperage.

7. Plasma arc cutting parameters have impact on cut quality and cutting parameters should be chosen according parts purposes. By using conclusions 1-6 is possible to understand how cutting parameters could affect cut quality and lower or higher meanings of cutting speed and amperage should be chosen for cutting.

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APPENDIX

1. Results of surface roughness measurements

Table 1A.1. Results of hardness measurements of work piece No. 1

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	173.55	HV/10	10x	0.3190	0.3347	HV	10
Admin	2016	December	VICKERS	144.94	HV/10	10x	0.3500	0.3653	HV	10
Admin	2016	December	VICKERS	136.05	HV/10	10x	0.3609	0.3774	HV	10
Admin	2016	December	VICKERS	139.10	HV/10	10x	0.3568	0.3734	HV	10
Admin	2016	December	VICKERS	137.40	HV/10	10x	0.3591	0.3756	HV	10
Admin	2016	December	VICKERS	133.40	HV/10	10x	0.3675	0.3781	HV	10
Admin	2016	December	VICKERS	134.15	HV/10	10x	0.3665	0.3770	HV	10
Admin	2016	December	VICKERS	133.86	HV/10	10x	0.3700	0.3743	HV	10
Admin	2016	December	VICKERS	133.41	HV/10	10x	0.3731	0.3725	HV	10
Admin	2016	December	VICKERS	129.86	HV/10	10x	0.3724	0.3793	HV	10

Table 1A.2. Results of hardness measurements of work piece No. 2

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	185.96	HV/10	10x	0.3132	0.3183	HV	10
Admin	2016	December	VICKERS	148.34	HV/10	10x	0.3467	0.3604	HV	10
Admin	2016	December	VICKERS	134.94	HV/10	10x	0.3631	0.3749	HV	10
Admin	2016	December	VICKERS	131.63	HV/10	10x	0.3690	0.3778	HV	10
Admin	2016	December	VICKERS	133.83	HV/10	10x	0.3651	0.3793	HV	10
Admin	2016	December	VICKERS	133.54	HV/10	10x	0.3676	0.3776	HV	10
Admin	2016	December	VICKERS	130.44	HV/10	10x	0.3715	0.3825	HV	10
Admin	2016	December	VICKERS	130.91	HV/10	10x	0.3713	0.3814	HV	10
Admin	2016	December	VICKERS	131.71	HV/10	10x	0.3689	0.3815	HV	10
Admin	2016	December	VICKERS	130.69	HV/10	10x	0.3714	0.3819	HV	10

Table 1A.3. Results of hardness measurements of work piece No. 3

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	159.37	HV/10	10x	0.3332	0.3490	HV	10
Admin	2016	December	VICKERS	151.79	HV/10	10x	0.3417	0.3573	HV	10
Admin	2016	December	VICKERS	138.85	HV/10	10x	0.3624	0.3684	HV	10
Admin	2016	December	VICKERS	135.97	HV/10	10x	0.3634	0.3751	HV	10
Admin	2016	December	VICKERS	129.01	HV/10	10x	0.3754	0.3793	HV	10
Admin	2016	December	VICKERS	132.51	HV/10	10x	0.3675	0.3773	HV	10
Admin	2016	December	VICKERS	130.17	HV/10	10x	0.3723	0.3825	HV	10
Admin	2016	December	VICKERS	130.66	HV/10	10x	0.3716	0.3818	HV	10
Admin	2016	December	VICKERS	129.36	HV/10	10x	0.3736	0.3835	HV	10
Admin	2016	December	VICKERS	131.12	HV/10	10x	0.3714	0.3806	HV	10

Table 1A.4. Results of hardness measurements of work piece No. 4

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	164.94	HV/10	10x	0.3309	0.3396	HV	10
Admin	2016	December	VICKERS	148.14	HV/10	10x	0.3474	0.3601	HV	10
Admin	2016	December	VICKERS	145.92	HV/10	10x	0.3512	0.3617	HV	10
Admin	2016	December	VICKERS	136.45	HV/10	10x	0.3598	0.3774	HV	10
Admin	2016	December	VICKERS	133.63	HV/10	10x	0.3631	0.3783	HV	10
Admin	2016	December	VICKERS	130.08	HV/10	10x	0.3714	0.3798	HV	10
Admin	2016	December	VICKERS	129.79	HV/10	10x	0.3728	0.3831	HV	10
Admin	2016	December	VICKERS	130.28	HV/10	10x	0.3707	0.3838	HV	10
Admin	2016	December	VICKERS	129.17	HV/10	10x	0.3696	0.3881	HV	10
Admin	2016	December	VICKERS	127.95	HV/10	10x	0.3751	0.3863	HV	10

Table 1A.5. Results of hardness measurements of work piece No. 5

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	195.52	HV/10	10x	0.3154	0.3005	HV	10
Admin	2016	December	VICKERS	173.48	HV/10	10x	0.3250	0.3289	HV	10
Admin	2016	December	VICKERS	149.00	HV/10	10x	0.3490	0.3565	HV	10
Admin	2016	December	VICKERS	144.84	HV/10	10x	0.3559	0.3597	HV	10
Admin	2016	December	VICKERS	137.92	HV/10	10x	0.3638	0.3695	HV	10
Admin	2016	December	VICKERS	136.57	HV/10	10x	0.3616	0.3753	HV	10
Admin	2016	December	VICKERS	134.38	HV/10	10x	0.3685	0.3744	HV	10
Admin	2016	December	VICKERS	130.66	HV/10	10x	0.3729	0.3768	HV	10
Admin	2016	December	VICKERS	130.11	HV/10	10x	0.3737	0.3812	HV	10
Admin	2016	December	VICKERS	128.67	HV/10	10x	0.3741	0.3851	HV	10

Table 1A.6. Results of hardness measurements of work piece No. 6

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	170.57	HV/10	10x	0.3279	0.3315	HV	10
Admin	2016	December	VICKERS	149.70	HV/10	10x	0.3519	0.3520	HV	10
Admin	2016	December	VICKERS	141.00	HV/10	10x	0.3571	0.3645	HV	10
Admin	2016	December	VICKERS	138.01	HV/10	10x	0.3620	0.3710	HV	10
Admin	2016	December	VICKERS	135.86	HV/10	10x	0.3631	0.3724	HV	10
Admin	2016	December	VICKERS	134.41	HV/10	10x	0.3712	0.3716	HV	10
Admin	2016	December	VICKERS	131.96	HV/10	10x	0.3695	0.3764	HV	10
Admin	2016	December	VICKERS	133.19	HV/10	10x	0.3685	0.3739	HV	10
Admin	2016	December	VICKERS	132.54	HV/10	10x	0.3717	0.3763	HV	10
Admin	2016	December	VICKERS	131.33	HV/10	10x	0.3715	0.3800	HV	10

Table 1A.7. Results of hardness measurements of work piece No. 7

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	187.20	HV/10	10x	0.3059	0.3235	HV	10
Admin	2016	December	VICKERS	161.96	HV/10	10x	0.3331	0.3435	HV	10
Admin	2016	December	VICKERS	144.97	HV/10	10x	0.3501	0.3651	HV	10
Admin	2016	December	VICKERS	142.58	HV/10	10x	0.3552	0.3660	HV	10
Admin	2016	December	VICKERS	136.41	HV/10	10x	0.3643	0.3730	HV	10
Admin	2016	December	VICKERS	135.89	HV/10	10x	0.3643	0.3745	HV	10
Admin	2016	December	VICKERS	130.87	HV/10	10x	0.3714	0.3813	HV	10
Admin	2016	December	VICKERS	132.88	HV/10	10x	0.3692	0.3778	HV	10
Admin	2016	December	VICKERS	130.78	HV/10	10x	0.3735	0.3795	HV	10
Admin	2016	December	VICKERS	130.91	HV/10	10x	0.3746	0.3780	HV	10

Table 1A.8. Results of hardness measurements of work piece No. 8

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	174.34	HV/5	10x	0.2276	0.2336	HV	5
Admin	2016	December	VICKERS	143.09	HV/5	10x	0.2532	0.2547	HV	5
Admin	2016	December	VICKERS	135.17	HV/5	10x	0.2596	0.2631	HV	5
Admin	2016	December	VICKERS	133.67	HV/5	10x	0.2631	0.2626	HV	5
Admin	2016	December	VICKERS	137.20	HV/5	10x	0.2586	0.2613	HV	5
Admin	2016	December	VICKERS	137.74	HV/5	10x	0.2576	0.2601	HV	5
Admin	2016	December	VICKERS	135.72	HV/5	10x	0.2601	0.2616	HV	5
Admin	2016	December	VICKERS	134.96	HV/5	10x	0.2596	0.2635	HV	5
Admin	2016	December	VICKERS	137.84	HV/5	10x	0.2571	0.2606	HV	5
Admin	2016	December	VICKERS	135.52	HV/5	10x	0.2576	0.2655	HV	5

Table 1A.9. Results of hardness measurements of work piece No. 9

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	174.78	HV/10	10x	0.3291	0.3212	HV	10
Admin	2016	December	VICKERS	148.72	HV/10	10x	0.3500	0.3561	HV	10
Admin	2016	December	VICKERS	139.46	HV/10	10x	0.3640	0.3635	HV	10
Admin	2016	December	VICKERS	137.93	HV/10	10x	0.3655	0.3660	HV	10
Admin	2016	December	VICKERS	135.45	HV/10	10x	0.3655	0.3729	HV	10
Admin	2016	December	VICKERS	135.43	HV/10	10x	0.3690	0.3695	HV	10
Admin	2016	December	VICKERS	135.40	HV/10	10x	0.3685	0.3700	HV	10
Admin	2016	December	VICKERS	135.78	HV/10	10x	0.3680	0.3695	HV	10
Admin	2016	December	VICKERS	136.13	HV/10	10x	0.3685	0.3680	HV	10
Admin	2016	December	VICKERS	136.30	HV/10	10x	0.3685	0.3675	HV	10

Table 1A.10. Results of hardness measurements of work piece No. 10

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	173.42	HV/10	10x	0.3271	0.3268	HV	10
Admin	2016	December	VICKERS	139.85	HV/10	10x	0.3591	0.3675	HV	10
Admin	2016	December	VICKERS	136.07	HV/10	10x	0.3685	0.3680	HV	10
Admin	2016	December	VICKERS	134.59	HV/10	10x	0.3690	0.3719	HV	10
Admin	2016	December	VICKERS	132.47	HV/10	10x	0.3729	0.3734	HV	10
Admin	2016	December	VICKERS	132.51	HV/10	10x	0.3739	0.3724	HV	10
Admin	2016	December	VICKERS	131.42	HV/10	10x	0.3729	0.3764	HV	10
Admin	2016	December	VICKERS	131.47	HV/10	10x	0.3727	0.3784	HV	10
Admin	2016	December	VICKERS	131.70	HV/10	10x	0.3719	0.3768	HV	10
Admin	2016	December	VICKERS	132.02	HV/10	10x	0.3708	0.3786	HV	10

Table 1A.11. Results of hardness measurements of work piece No. 11

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	159.27	HV/10	10x	0.3459	0.3365	HV	10
Admin	2016	December	VICKERS	142.46	HV/10	10x	0.3601	0.3596	HV	10
Admin	2016	December	VICKERS	138.83	HV/10	10x	0.3644	0.3665	HV	10
Admin	2016	December	VICKERS	135.20	HV/10	10x	0.3680	0.3709	HV	10
Admin	2016	December	VICKERS	137.38	HV/10	10x	0.3695	0.3631	HV	10
Admin	2016	December	VICKERS	136.67	HV/10	10x	0.3675	0.3675	HV	10
Admin	2016	December	VICKERS	136.22	HV/10	10x	0.3673	0.3705	HV	10
Admin	2016	December	VICKERS	134.46	HV/10	10x	0.3702	0.3725	HV	10
Admin	2016	December	VICKERS	134.09	HV/10	10x	0.3660	0.3759	HV	10
Admin	2016	December	VICKERS	133.22	HV/10	10x	0.3690	0.3754	HV	10

Table 1A.12. Results of hardness measurements of work piece No. 12

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	199.88	HV/10	10x	0.2996	0.3095	HV	10
Admin	2016	December	VICKERS	152.15	HV/10	10x	0.3446	0.3535	HV	10
Admin	2016	December	VICKERS	145.05	HV/10	10x	0.3532	0.3618	HV	10
Admin	2016	December	VICKERS	140.12	HV/10	10x	0.3611	0.3645	HV	10
Admin	2016	December	VICKERS	137.55	HV/10	10x	0.3660	0.3665	HV	10
Admin	2016	December	VICKERS	137.57	HV/10	10x	0.3655	0.3670	HV	10
Admin	2016	December	VICKERS	138.14	HV/10	10x	0.3655	0.3655	HV	10
Admin	2016	December	VICKERS	135.35	HV/10	10x	0.3670	0.3714	HV	10
Admin	2016	December	VICKERS	136.77	HV/10	10x	0.3654	0.3709	HV	10
Admin	2016	December	VICKERS	135.91	HV/10	10x	0.3670	0.3700	HV	10

Table 1A.13. Results of hardness measurements of work piece No. 13

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	181.54	HV/10	10x	0.3158	0.3217	HV	10
Admin	2016	December	VICKERS	143.19	HV/10	10x	0.3567	0.3611	HV	10
Admin	2016	December	VICKERS	135.70	HV/10	10x	0.3665	0.3709	HV	10
Admin	2016	December	VICKERS	133.20	HV/10	10x	0.3719	0.3724	HV	10
Admin	2016	December	VICKERS	130.66	HV/10	10x	0.3743	0.3791	HV	10
Admin	2016	December	VICKERS	130.98	HV/10	10x	0.3709	0.3798	HV	10
Admin	2016	December	VICKERS	132.81	HV/10	10x	0.3729	0.3724	HV	10
Admin	2016	December	VICKERS	130.47	HV/10	10x	0.3754	0.3764	HV	10
Admin	2016	December	VICKERS	135.26	HV/10	10x	0.3700	0.3685	HV	10
Admin	2016	December	VICKERS	132.92	HV/10	10x	0.3690	0.3768	HV	10

Table 1A.14. Results of hardness measurements of work piece No. 14

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2016	December	VICKERS	182.21	HV/10	10x	0.3182	0.3197	HV	10
Admin	2016	December	VICKERS	145.82	HV/10	10x	0.3570	0.3561	HV	10
Admin	2016	December	VICKERS	131.46	HV/10	10x	0.3690	0.3803	HV	10
Admin	2016	December	VICKERS	128.28	HV/10	10x	0.3754	0.3833	HV	10
Admin	2016	December	VICKERS	128.75	HV/10	10x	0.3768	0.3803	HV	10
Admin	2016	December	VICKERS	129.42	HV/10	10x	0.3749	0.3803	HV	10
Admin	2016	December	VICKERS	128.94	HV/10	10x	0.3778	0.3788	HV	10
Admin	2016	December	VICKERS	129.03	HV/10	10x	0.3753	0.3828	HV	10
Admin	2016	December	VICKERS	129.88	HV/10	10x	0.3773	0.3764	HV	10
Admin	2016	December	VICKERS	129.47	HV/10	10x	0.3823	0.3729	HV	10

Table 1A.15. Results of hardness measurements of work piece No. 15

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2017	April	VICKERS	186.31	HV/10	10x	0.3177	0.3113	HV	10
Admin	2017	April	VICKERS	170.82	HV/10	10x	0.3315	0.3251	HV	10
Admin	2017	April	VICKERS	166.63	HV/10	10x	0.3345	0.3305	HV	10
Admin	2017	April	VICKERS	168.27	HV/10	10x	0.3320	0.3296	HV	10
Admin	2017	April	VICKERS	163.32	HV/10	10x	0.3369	0.3345	HV	10
Admin	2017	April	VICKERS	166.15	HV/10	10x	0.3330	0.3325	HV	10
Admin	2017	April	VICKERS	164.41	HV/10	10x	0.3365	0.3325	HV	10
Admin	2017	April	VICKERS	165.82	HV/10	10x	0.3355	0.3305	HV	10
Admin	2017	April	VICKERS	165.09	HV/10	10x	0.3355	0.3320	HV	10
Admin	2017	April	VICKERS	165.95	HV/10	10x	0.3325	0.3330	HV	10

Table 1A.16. Results of hardness measurements of work piece No. 16

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2017	April	VICKERS	195.87	HV/10	10x	0.3118	0.3035	HV	10
Admin	2017	April	VICKERS	182.65	HV/10	10x	0.3221	0.3151	HV	10
Admin	2017	April	VICKERS	175.79	HV/10	10x	0.3274	0.3221	HV	10
Admin	2017	April	VICKERS	163.78	HV/10	10x	0.3414	0.3315	HV	10
Admin	2017	April	VICKERS	160.70	HV/10	10x	0.3438	0.3355	HV	10
Admin	2017	April	VICKERS	160.94	HV/10	10x	0.3414	0.3374	HV	10
Admin	2017	April	VICKERS	164.02	HV/10	10x	0.3384	0.3340	HV	10
Admin	2017	April	VICKERS	163.29	HV/10	10x	0.3414	0.3325	HV	10
Admin	2017	April	VICKERS	162.82	HV/10	10x	0.3419	0.3330	HV	10
Admin	2017	April	VICKERS	157.02	HV/10	10x	0.3502	0.3369	HV	10

Table 1A.17. Results of hardness measurements of work piece No. 17

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2017	April	VICKERS	184.66	HV/10	10x	0.3212	0.3123	HV	10
Admin	2017	April	VICKERS	171.61	HV/10	10x	0.3305	0.3266	HV	10
Admin	2017	April	VICKERS	167.04	HV/10	10x	0.3335	0.3325	HV	10
Admin	2017	April	VICKERS	159.12	HV/10	10x	0.3458	0.3365	HV	10
Admin	2017	April	VICKERS	160.96	HV/10	10x	0.3389	0.3394	HV	10
Admin	2017	April	VICKERS	157.95	HV/10	10x	0.3438	0.3409	HV	10
Admin	2017	April	VICKERS	165.37	HV/10	10x	0.3374	0.3315	HV	10
Admin	2017	April	VICKERS	162.48	HV/10	10x	0.3424	0.3325	HV	10
Admin	2017	April	VICKERS	161.75	HV/10	10x	0.3414	0.3350	HV	10
Admin	2017	April	VICKERS	157.95	HV/10	10x	0.3414	0.3429	HV	10

Table 1A.18. Results of hardness measurements of work piece No. 18

Operator	Year	Month	Method	Result	Scale	Objective	d1	d2	Indentor	Force
Admin	2017	April	VICKERS	195.28	HV/10	10x	0.3045	0.3118	HV	10
Admin	2017	April	VICKERS	179.74	HV/10	10x	0.3238	0.3185	HV	10
Admin	2017	April	VICKERS	173.34	HV/10	10x	0.3261	0.3266	HV	10
Admin	2017	April	VICKERS	167.78	HV/10	10x	0.3350	0.3286	HV	10
Admin	2017	April	VICKERS	164.97	HV/10	10x	0.3369	0.3320	HV	10
Admin	2017	April	VICKERS	167.64	HV/10	10x	0.3315	0.3320	HV	10
Admin	2017	April	VICKERS	168.00	HV/10	10x	0.3345	0.3286	HV	10
Admin	2017	April	VICKERS	167.39	HV/10	10x	0.3320	0.3320	HV	10
Admin	2017	April	VICKERS	166.66	HV/10	10x	0.3335	0.3320	HV	10
Admin	2017	April	VICKERS	163.70	HV/10	10x	0.3394	0.3320	HV	10