KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

**Egidijus Stonkus**

# RESEARCH OF HEAT AFFECTED ZONE AFTER CUTTING IN HARDOX STEEL

Final project for Master degree

**Supervisor**
Dr. Lina Kavaliauskienė

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**Industrial Engineering and Management (code M5106L21)**

**Supervisor**
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**KAUNO TECHNOLOGIJOS UNIVERSITETAS**
**MECHANIKOS INŽINERIJOS IR DIZAINO FAKULTETAS**

**Tvirtinu:**
Gamybos inžinerijos katedros vedėjas

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*(parašas, data)*

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*(vardas, pavardė)*

**MAGISTRANTŪROS STUDIJŲ BAIGIAMOJO DARBO UŽDUOTIS**
**Studijų programa PRAMONĖS INŽINERIJA IR VADYBA**

Magistrantūros studijų, kurias baigus įgyjamas magistro kvalifikacinis laipsnis, baigiamasis darbas yra mokslinio tiriamojo ar taikomojo pobūdžio darbas (projektas), kuriam atlikti ir apginti skiriama 30 kreditų. Šiuo darbu studentas turi parodyti, kad yra pagilinęs ir papildęs pagrindinėse studijose įgytas žinias, yra įgijęs pakankamai gebėjimų formuluoti ir spręsti aktualią problemą, turėdamas ribotą ir (arba) prieštaringą informaciją, savarankiškai atlikti mokslinius ar taikomuosius tyrimus ir tinkamai interpretuoti duomenis. Baigiamuoju darbu bei jo gynimu studentas turi parodyti savo kūrybingumą, gebėjimą taikyti fundamentines mokslo žinias, socialinės bei komercinės aplinkos, teisės aktų ir finansinių galimybių išmanymą, informacijos šaltinių paieškos ir kvalifikuotos jų analizės įgūdžius, skaičiuojamųjų metodų ir specializuotos programinės įrangos bei bendrosios paskirties informacinių technologijų naudojimo įgūdžius, taisyklingos kalbos vartosenos įgūdžius, gebėjimą tinkamai formuluoti išvadas.

1. Darbo tema Hardox plieno, pjauto skirtingais būdais, terminių zonų tyrimas

Patvirtinta 2015 m. gegužės mėn. 11 d. dekano įsakymu Nr. ST17-F-11-2

2. Darbo tikslas Ištirti Harox plieno, pjauto skirtingais pjovimo būdais termines zonas, siekiant surasti optimaliausią gamybos būdą.

3. Darbo struktūra Antraštinis lapas, akaedminio sąžiningumo deklaracija, santraukos lietuvių ir anglų kalbomis, baigiamojo darbo užduotis, turinys, įvadas, teorinė dalis, tiriamoji dalis, ekonominė dalis, išvados, literatūros sąrašas, priedai.

4. Reikalavimai ir sąlygos

1) Apžvelgti hardox plieno pjovimo technologijas

1) Atlikti terminio poveikio zonų mikrokietumo bandymus.

2) Analizuojant realią detalę, atlikti ekonominį vertinimą.

5. Darbo pateikimo terminas 2015m. gegužės mėn. 20 d.

6. Ši užduotis yra neatskiriama baigiamojo darbo dalis

Išduota studentui Egidijui Stonkui

Užduotį gavau ____________________ ____________________
(studento vardas, pavardė) (parašas, data)

Vadovas ____________________ ____________________
(pareigos, vardas, pavardė) (parašas, data)

KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

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EGIDIJUS STONKUS

(Student's name, surname)

Industrial Engineering and Management (code M5106L21)

(Title and code of study programme)

**Research of Heat Affected Zone After Cutting in HARDOX Steel**

**DECLARATION OF ACADEMIC HONESTY**

2015 May 13

Kaunas

I confirm that a final project by me, **Egidijus Stonkus**, on the subject " **Research of Heat Affected Zone After Cutting in HARDOX Steel** " is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

I understand that in case of a resurfaced fact of dishonesty penalties will be applied to me according to the procedure effective at Kaunas University of Technology.

*(name and surname filled in by hand)* *(signature)*

Stonkus, E. Research of Heat Affected Zone After Cutting in HARDOX Steel. *Mechanical engineering Master's degree* final project / supervisor Dr. Lina Kavaliauskienė; Kaunas University of Technology, Faculty of Mechanical Engineering and Design, department of Production Engineering.

Kaunas, 2015. 44 p.

**SUMMARY**

This Master's degree thesis covers analysis, research and economical calculations regarding wear-resistant steel brand HARDOX. Analysis of possible blank production methods is described and possibilities of production using laser, plasma, gas or water-abrasive jet cutting machines are described.

Extensive research of heat affected zones is carried due to the fact, that most of the cutting methods are thermal and, therefore, change internal microstructure of steel. Research is carried out for thicknesses from 5 to 15mm, specimens are produced using different cutting machines. Microindentation test results show changing hardness from cutting edge to inside. Summary graphs enable to forecast size of heat affected zone for other thicknesses, which have not been tested.

Example of economical calculations is created using simple real-life part as basis. Prices of different materials, production methods are calculated along with price calculation of heat affected zone. Same procedures can be applied to other parts as well to determine economical background and discover most beneficial production method.

Stonkus, E. Hardox plieno, pjauto skirtingais pjovimo būdais, terminių zonų tyrimas. *Mechanikos inžinerijos magistro laipsniu* baigiamasis darbas / darbo vadovė Dr. Lina Kavaliauskienė; Kauno Technologijų Universitetas, Mechanikos inžinerijos ir dizaino fakultetas, Gamybos Inžinerijos katedra.

Kaunas, 2015. 44 psl.

## SANTRAUKA


Šiame, magistro laipsnį suteikiančiame, darbe aprašoma trinčiai atspariojo Hardox markės plieno analizė, tyrimas bei ekonominiai skaičiavimai. Analizuojami galimi ruošinių bei galutinių detalių gamybos būdai naudojant lazerinio, plazmines, dujines bei vandens – abrazyvo pjovimo įrengimus.

Ypatingas dėmesys skiriamas po karšto pjovimo atsiradusių terminio poveikio zonų tyrimui. Tiriami įvairūs ruošiniai, išpjauti skirtingais pjovimo būdais, kurių storis nuo 5 iki 15mm. Mikrokietumo matavimų rezultatai rodo medžiagos kietumo kitimą nuo pjautos briaunos iki terminio poveikio zonos pabaigos – taip išmatuoti zonų pločiai. Iš gautų rezultatų sudarytos kreivės leidžia nuspėti terminio poveikio zonų dydžius kitų storių bandiniams.

Ekonominio skaičiavimo pavyzdys buvo sukurtas naudojant realią detalę ir rinkos kainas. Šioje dalyje buvo suskaičiuotos medžiagų ir gamybos kainos, taip pat pinigine išraiška įvertintos terminės zonos kaip amortizaciniai nuostoliai. Tokia ekonominio analizavimo metodika gali būti taikoma įvairioms detalėms, siekiant parinkti optimaliausią gamybos kelią.

**CONTENTS**

# INTRODUCTION

A lot of modern companies define different goals in order to be unique and in this way to expand and grow in their market. But most of them have a goal for their production like sustainability, reliability or environmentally-friendly. In order to achieve any of these goals, companies must follow state-of-the-art technological processes or invest in most modern manufacturing machines. These machines are the key in improving working efficiency, as well as decreasing production costs and helping to achieve previously written goals. One has to know, that different approach also exists. It is based on knowledge about materials, knowledge about innovations and breakthroughs in material manufacturing and the knowledge of how and where apply them.

Choosing best material for specific part is crucial, since many alternatives exist. For example, one can choose stronger steel or lighter aluminum for housing, cheaper mild steel or more expensive, but durable wear-resistant steel and so on. Choosing right material and right processing technique should be weighed according to several factors.

Main goal:

To study heat affected zone of Hardox steel after cutting in order to find best and most cost-effective cutting solution for production optimization.

Main tasks:

1. Analyze possible blank cutting methods.
2. Study heat affected zones after cutting.
3. Analyze possible production methods based on quality and cost.

# 1. OVERVIEW OF SCIENTIFIC AND TECHNOLOGICAL LITERATURE

Definitions:

Wear resistant steel – type of steel, specifically made to withstand abrasive wear.

Steel – alloy of iron and carbon (0,08 ÷ 2,14%).

HAZ – Heat affected zone

Kerf - A groove, slit, or notch made by a cutting tool, such as a laser cutter or the width of a groove made by a laser cutting tool. Figure 2.1. represent schematic definition.

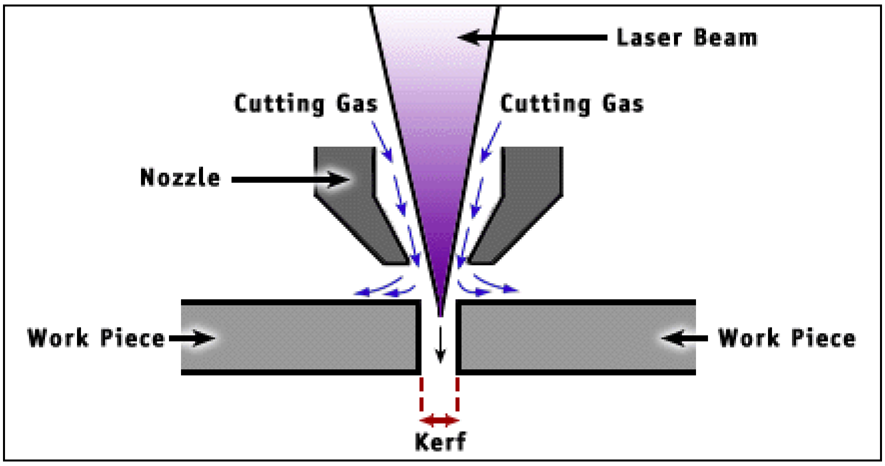



Figure 2.1. Schematic definition of Kerf [1]

## 1.1.Steel Hardox – General properties.

Material to be analysed is HARDOX steel. It is brand name referring to special wear (abrasion) resistant steel, made by Swedish Steel AB (SSAB) [2]. It has similar properties to carbon steel, which has been heat-processed in order to increase its hardness and abrasion resistance. But its appeal is in ready-made properties for sheet metal profile of analyzed steel. Manufacturer (SSAB) is selling this steel already heat-processed with provided physical properties. Using this steel eliminates need for hardening and tempering using conventional methods like furnace heating and following procedures. In some cases (especially in small production batches) cutting parts from sheets of HARDOX is less expensive, than cutting using same machines from common carbon steel and then heat-treating it. Also, cutting from this type of processed steel can reduce, or completely eliminate unwanted procedures like straightening of part, deformed or warped after heat-treatment. HARDOX steel product range is based on hardness (HBW) of steel type. Product range is given in Fig. 2.2. [3].

| Steel grade | Hardness Nominal [HBW] | Impact toughness CVL typical 20 mm | Bending properties Transverse t < 8 mm R/t | Rel. service life interval[1] | CEV/CET[2] Typical 20 mm | Thickness [mm] |
|---|---|---|---|---|---|---|
| **Hardox** – Workshop friendly abrasion resistant wear plates for all purposes, enabling lighter, stronger and more durable applications. | | | | | | |
| Hardox HiTuf | 350 | 95 J – 40 °C[3] | | | 0.55/0.36[3] | 40–160 |
| Hardox 400 | 400 | 45 J – 40 °C | 2.5 | 1 | 0.37/0.27 | 3–130[4] |
| Hardox 450 | 450 | 50 J – 40 °C | 3.5 | 1.1–1.7 | 0.47/0.34 | 3–130 |
| Hardox 450 | 450[5] | | 4.0 | | 0.39/0.31 | 0.7–2.1 |
| Hardox 500 | 500 | 37J – 40 °C | 4.0 | 1.3–2.1 | 0.62/0.41 | 4–80 |
| Hardox 550 | 550 | 30 J – 40 °C | | 1.5–4.0 | 0.72/0.48 | 10–51 |
| Hardox 600 | 600 | 20 J – 40 °C | | 1.8–8.0 | 0.73/0.55 | 8–51 |
| Hardox Extreme | 650–700 | < 15 J – 40 °C | | 2.0–18.0 | 0.84/0.59 | 8–19 |

Fig. 2.2. HARDOX steel product range, given by manufacturer [3].

Parts, made from this steel can be used in various applications – from recycling to mining. Almost any part that has sliding, impact or squeezing wear can be made from this steel, which ensures its longer life. One of the most popular applications for this steel is tipper or dump truck body parts [7]. Hardox is tougher and harder steel compared to structural, so structures made of Hardox will last longer and weigh less at the same time, allowing for increased productivity and product performance.

## 1.2.Chemical composition

Mechanical properties of steel are usually determined by its chemical composition [4;5]. Various alloying elements give different results. It is known that carbon increases strength and gives possibility to further process steel and increase its hardness by heat-treatment [4]. Alloy must have minimum carbon content for heat-treatment to be effective [6]. Figure 2.3. shows hardness dependence to carbon content. But increasing carbon will make it brittle which in some cases is unwished property. Hardox has also other alloying elements which increase hardness and toughness. Table 2.1. shows chemical composition of two Hardox grades and other popular grades with comparison to one grade of structural steel.

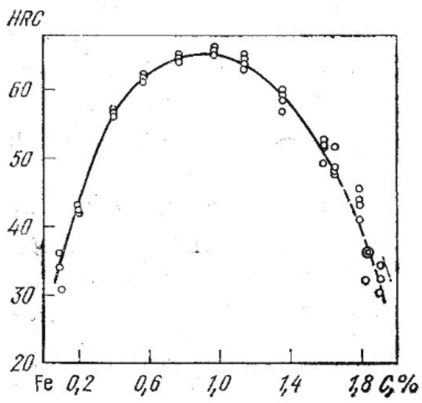



Figure 2.3. Graph of hardness dependency to carbon quantity in steel alloy [4]

Table 2.1. Chemical composition of different steel grades

| Compound / Grade | C, Max% | Si, Max% | Mn, Max% | P, Max% | S, Max% | Cr, Max% | Ni, Max% | Mo, Max% | B, Max% |
|---|---|---|---|---|---|---|---|---|---|
| HARDOX 450 | 0.26 | 0.7 | 1.6 | 0.025 | 0.01 | 1.4 | 1.5 | 0.6 | 0.005 |
| HARDOX 600 | 0.47 | 0.7 | 1 | 0.015 | 0.01 | 1.2 | 2.5 | 0.7 | 0.005 |
| C45 (LST EN ISO) | 0.5 | 0.4 | 0.8 | 0.045 | 0.045 | 0.4 | 0.4 | 0.1 | N/S* |
| C60 (LST EN ISO) | 0.65 | 0.4 | 0.9 | 0.045 | 0.045 | 0.4 | 0.4 | 0.1 | N/S* |
| S355J2G3 (LST EN ISO) | 0.22 | 0.55 | 1.6 | 0.035 | 0.035 | 0.3 | 0.3 | 0.08 | N/S* |

N/S* - not specified

Table shows that main alloying elements are Manganese, Cromium and Nickel which change internal structure of steel to increase its durability but maintain flexibility. Hardox steel has higher tensile strength and hardness in Brinells but it is more flexible due to alloying elements rather than just an increase of carbon.

**HARDNESS COMPARISON OF SOME HARDOX GRADES***

| Brinell HBW 10 mm 29.4 kN | Vickers 98 N | Rockwell HRC | Approximate tensile strength MPa | Approximate corresponding grade |
|---|---|---|---|---|
| 400 | 401 | 40 | 1245 | Hardox 400 |
| 450 | 458 | 44.5 | 1412 | Hardox 450 |
| 500 | 514 | 49 | 1580 | Hardox 500 |
| 600 | 627 | 55 | 1940 | Hardox 600 |

* Tested by SSAB on standard production samples. The data is to be used as a guidance and not as a basis for design and acceptance testing.

Figure 2.4. Hardness comparison of some Hardox grades [3]

Table 2.2. Hardness and Yield strength of different steel grades

| Grade \ Property | HBW, Max | Yield strength |
|---|---|---|
| C45 (LST EN ISO) | 255 | 1030 |
| C60 (LST EN ISO) | 269 | 1130 |
| S355J2G3 (LST EN ISO) | 147 | 315 |

Hardox steel manufacturer SSAB has also correspondingly developed special manufacturing process which ensures high quality, homogenous structure and flatness. These properties are very important while processing steel by various cutting or machining machines.

## 1.3.Mechanical processing of Hardox steel

### 1.3.1. Cutting – general information

“HARDOX wear plate can very well be cut using both cold and thermal cutting methods. The cold methods are abrasive water jet cutting, shearing, sawing or abrasive grinding, while thermal methods are oxy-fuel, plasma and laser cutting.”[8]. General features for different cutting methods are shown in Fig. 2.5.

| Cutting method | Cutting speed | Kerf | HAZ | Dim. tolerance |
|---|---|---|---|---|
| Abrasive water-jet cutting | 8–150 mm/min | 1–3 mm | 0 mm | ±0,2 mm |
| Laser cutting | 600–2200 mm/min | <1 mm | 0,4–3 mm | ±0,2 mm |
| Plasma cutting | 1200–6000 mm/min | 2–4 mm | 2–5 mm | ±1,0 mm |
| Gas cutting | 150–700 mm/min | 2–5 mm | 4–10 mm | ±2,0 mm |

Fig 2.5. General features for different cutting methods. Kerf – “The width of the groove made while cutting” [9]. HAZ – heat affected zone

These general features are given by manufacturer, and although being accurate, they do not provide enough information. For example, dimension tolerance is greatly determined by cutting machine. General characteristics for cutting machines will be discussed later.

### 1.3.2. Cutting – abrasive water-jet cutting

“A water jet cutter, also known as a water jet or waterjet, is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. The term abrasive jet refers specifically to the use of a mixture of water and abrasive to cut hard materials such as metal orgranite, while the terms pure waterjet and water-only cutting refer to waterjet cutting without the use of added abrasives, often used for softer materials such as wood or rubber.

Waterjet cutting is often used during fabrication of machine parts. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. Waterjet cutting is used in various industries, including mining and aerospace, for cutting, shaping, and reaming.“[10].

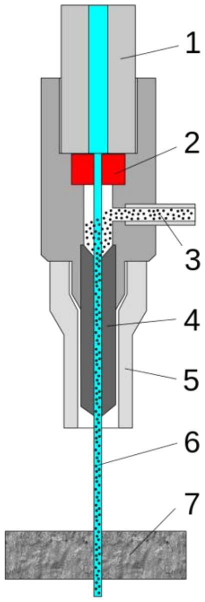



Fig. 2.6. A diagram of a water jet cutter: 1 - high-pressure water inlet, 2 - jewel (ruby or diamond), 3 - abrasive (garnet), 4 - mixing tube, 5 – guard, 6 - cutting water jet, 7 - cut material [10]

Working principle of water jet cutting machine is as follows: high pressure water jet comes from pumps through high-pressure water inlet to mixing chamber, where it is mixed with abrasive and released through nozzle. Machine has height sensors, to determine height of sheet material. Throughout cutting sensor moves down, to verify that material is flat, and moving cutting head will not hit anything and be damaged.

An important benefit of the water jet is the ability to cut material without interfering with its inherent structure, as there is no "heat-affected zone" (HAZ). Minimizing the effects of heat allows metals to be cut without harming or changing intrinsic properties.

Water jet cutters are also capable of producing intricate cuts in material. With specialized software and 3-D machining heads, complex shapes can be produced.[10]

Materials commonly cut with a water jet include rubber, foam, plastics, leather, composites, stone, tile, metals, food, paper and much more. Materials that cannot be cut with a water jet are tempered glass, diamonds, certain ceramics and certain types of plastics, which are hygroscopic.

Water jet cutting is one of the more expensive cutting machines, since a lot of energy is required for high-pressure pumps and abrasive sand adds up the price.

### 1.3.3. Cutting – laser cutting

„Laser cutting is a technology that uses a laser to cut materials, and is typically used for industrial manufacturing applications, but is also starting to be used by schools, small businesses, and hobbyists. Laser cutting works by directing the output of a high-power laser most commonly through optics. The laser optics and CNC (computer numerical control) are used to direct the material or the laser beam generated. A typical commercial laser for cutting materials would involve a motion control system to follow a CNC or G-code of the pattern to be cut onto the material. The focused laser beam directed at the material then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish. Industrial laser cutters are used to cut flat-sheet material as well as structural and piping materials." [11]

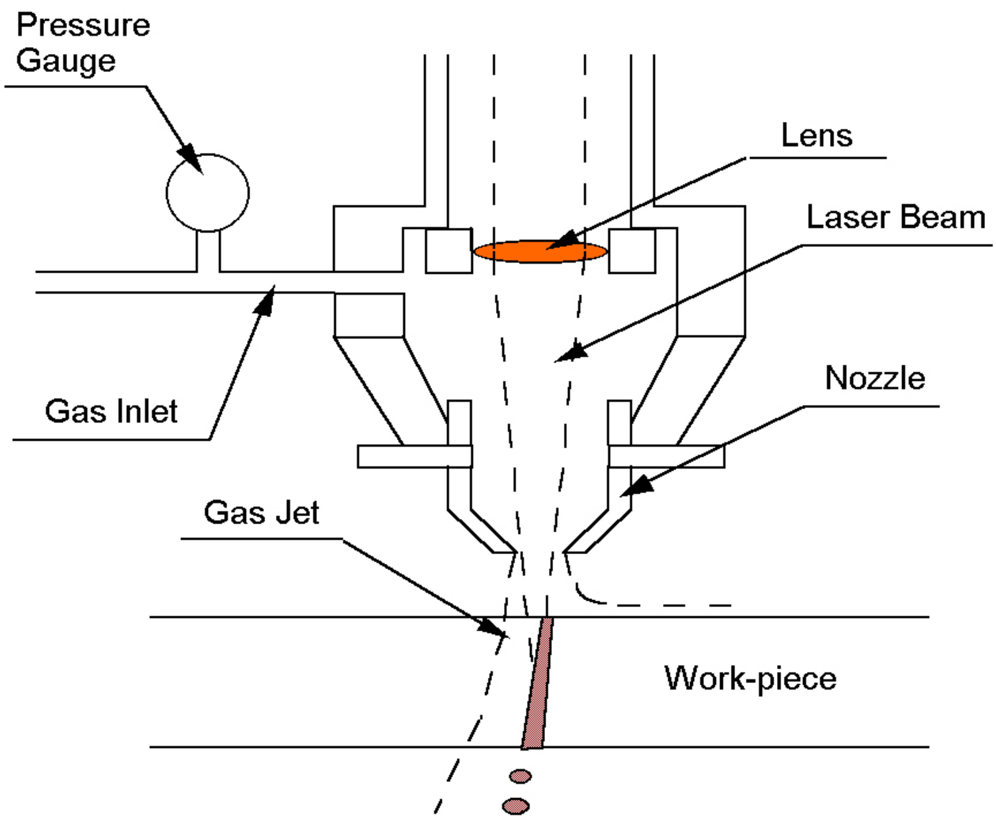



Fig. 2.7. Scheme of laser cutting machine cutting head [11]

Working principle of laser is as follows. Light is stimulated and its power increased by reflecting internally by means of partial mirror, until it achieves sufficient energy to escape as a stream of monochromatic coherent light. [11]. Mirrors direct laser beam to laser beam, which focuses light at the work zone. Focusing greatly determines cut quality and must be constantly adjusted to keep highest achievable cutting quality. Gases are purged to cutting area to help remove molten material from cutting zone, as well as to keep oxygen from entering cutting area and quickly oxidizing molten and heated material.

"Advantages of laser cutting over mechanical cutting include easier workholding and reduced contamination of workpiece (since there is no cutting edge which can become contaminated by the material or contaminate the material). Precision may be better, since the laser beam does not wear during the process. There is also a reduced chance of warping the material that is being cut, as laser systems have a small heat-affected zone. Some materials are also very difficult or impossible to cut by more traditional means."[11]

However, laser cutting machine cannot cut through very thick materials (>30mm), when plasma, water-jet or gas cutting machines can. Costs for cutting increase with the thickness of material, so when approaching maximum cutting capacity, costs of laser cutting can even be greater than plasma, gas or even water-jet.

Since laser cutting is based on melting or burning of material that is being cut, heat affects the part, and heat affected zones occur. Depth of zone depends on many variables, like cutting speed or chemical composition of material. [11] However, for this research, cutting speed will be ignored since aim of this research is different. Also manufacturer claims that cutting parameters are the same as structural steel due to its unique chemical composition.

### 1.3.4. Cutting – plasma and gas cutting

Two cutting types can be discussed in one chapter, since usually machines are same and cutting head can be easily modified or adjusted to change cutting type.

Plasma cutting refers to cutting process, which uses inert gas (in some units, compressed air), blown at high speed out of nozzle and electrical arc, formed through the same gases to create plasma. Plasma is sufficiently hot to melt the metal being cut and moves quickly enough to blow molten material away from cutting zone. [12]


Fig. 2.8. CNC plasma and flame cutting machine [12]

Gas or flame cutting refers to cutting process, similar to plasma cutting, with few differences. These are – types of gases being used (usually for flame cutting, Oxy Fuel Gas is used), combustion process (gases burn creating heat), and temperature, which is lower compared to plasma.

Kerf of both plasma and gas cutting types is much greater than laser or water jet. Since machine has to melt more metal, HAZ is wider. The width of the HAZ is influenced by:

- Cut speed – in general, faster speeds result in a smaller HAZ.
- Amperage (when using plasma) – for a given thickness of metal, a higher amperage (and consequently a faster cut speed) results in a smaller HAZ.
- The type of metal being cut. Different metals transfer heat at different rates and respond to differently to elevated temperatures. Increased temperatures and longer cutting times will result in a wider HAZ. As an example, a Plasma arc cutter can be used to cut any electrically-conductive material, but all things being equal it will create a different width HAZ on aluminum than on mild steel of the same thickness.

Another thing to note about the HAZ is that when cutting thicker metals the width of the zone may be smaller at the top of the cut edge and wider at the bottom.[13]

Upshot to this machine is cutting cost. Machine requires less energy for creating arc (plasma cutting) or creating and controlling burning gases, so cutting price, especially with thicker materials is much better, compared to other cutting types.

Cutting HARDOX® steel using discussed methods requires one more step, to reduce possibility of cut edge cracking. Cut edge cracking is a phenomenon that is closely related to hydrogen cracking in welds and occurs when thermal cutting methods are used. If cut edge cracks should occur, they will become visible between 48 hours and up to several weeks after cutting. So cut edge cracking can be regarded as delayed cracking. The risk of cut edge cracking increases with the steel hardness and plate thickness. [7]

Preheating prior to cutting is the best way of eliminating the risk of cut edge cracking. Preheating is most commonly applied prior to oxy-fuel cutting. Fig. 2.7. shows that preheating temperature depends on the steel grade and the plate thickness. Preheating can be carried out by means of burner laces, electric heating mats or by heating in a furnace. The required temperature should be measured on the opposite side from that at which heating takes place. [7]

| Grade | Plate thickness | Preheating temp. |
|---|---|---|
| HARDOX HiTuf | ≥90 mm | 100°C |
| HARDOX 400 | 45–59,9 mm<br>60 – 80 mm<br>>80 mm | 100°C<br>150°C<br>175°C |
| HARDOX 450 | 40– 49,9 mm<br>50 – 69,9 mm<br>70 - 80 mm | 100°C<br>150°C<br>175°C |
| HARDOX 500 | 30–49,9 mm<br>50 – 59,9 mm<br>60 – 80 mm | 100°C<br>150°C<br>175°C |
| HARDOX 550 | 20–50 mm | 150°C |
| HARDOX 600 | 12–29,9 mm<br>30–50 mm | 150°C<br>175°C |

Fig.2.7. Manufacturer recommendations on preheating temperature [8]

Another way of avoiding cut edge cracking is to maintain a low cutting speed. This could be an alternative if preheating cannot be carried out. Cutting at low speed is less reliable than preheating for preventing cut edge cracking.[7] For this situation manufacturer provides table with cutting speed restrictions, which is represented in Fig. 2.8.

| Plate thickness | HARDOX 400 | HARDOX 450 | HARDOX 500 | HARDOX 550 | HARDOX 600 |
|---|---|---|---|---|---|
| ≤12 mm | no restrictions | no restrictions | no restrictions | no restrictions | no restrictions |
| ≤15 mm | no restrictions | no restrictions | no restrictions | no restrictions | 300 mm/min |
| ≤20 mm | no restrictions | no restrictions | no restrictions | no restrictions | 200 mm/min |
| ≤25 mm | no restrictions | no restrictions | 300 mm/min | 270 mm/min | 180 mm/min |
| ≤30 mm | no restrictions | no restrictions | 250 mm/min | 230 mm/min | 150 mm/min |
| ≤35 mm | no restrictions | no restrictions | 230 mm/min | 190 mm/min | 140 mm/min |
| ≤40 mm | no restrictions | 230 mm/min | 200 mm/min | 160 mm/min | 130 mm/min |
| ≤45 mm | 230 mm/min | 200 mm/min | 170 mm/min | 140 mm/min | 120 mm/min |
| ≤50 mm | 210 mm/min | 180 mm/min | 150 mm/min | 130 mm/min | 110 mm/min |
| ≤60 mm | 200 mm/min | 170 mm/min | 140 mm/min | - | - |
| ≤70 mm | 190 mm/min | 160 mm/min | 135 mm/min | - | - |
| ≤80 mm | 180 mm/min | 150 mm/min | 130 mm/min | - | - |
| >80 mm | Preheating | - | - | - | - |

Fig. 2.8. Manufacturers recommendations for maximum cutting speed, mm/min to reduce cut edge cracking, if no preheating is employed in oxy-fuel cutting [8]

It has to be noted that When oxy-fuel is used for cutting 30 mm or thicker plate, the rule of thumb is that there is risk of loss of hardness of the entire component if the distance between two cuts is less than 200 mm. The best way of eliminating the risk of softening is to use cold cutting methods, such as abrasive water jet cutting. If thermal cutting must be performed, laser or plasma cutting is preferable to oxy-fuel cutting.

When small parts are cut by oxy-fuel from thick plate, there is risk of softening as well as cut edge cracking. Submerged cutting at low cutting speed is proposed solution [13]

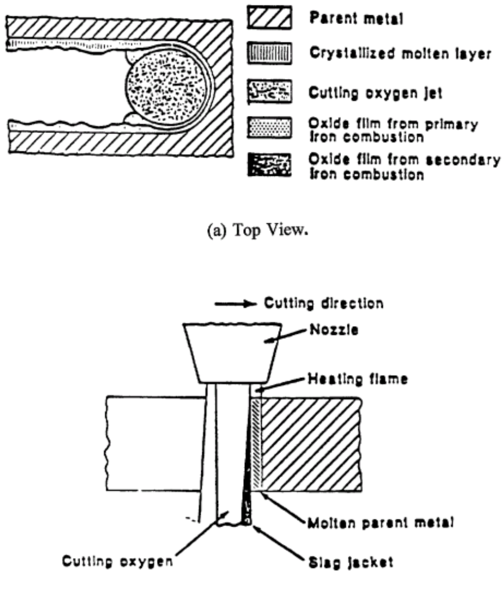
## 1.4.Heat affected zone analysis

It is difficult to find any synonymous researches that were carried out, especially for special steel. It is clear, that HAZ is described in various ways, but not the edge properties after thermal cutting. This is useful to know, as thermal cutting is is being used in manufacturing incisively and additional information about material allowances for machining should be acknowledged.

Clearly, any changes for simple structural steel are not so important as steel does not change its structure that much, compared to special “pre-heat-treated” steel. Example of special steel would be any grade of steel HARDOX, which is sold as sheets, already heat-treated. Additional knowledge of HAZ, especially in tandem with cutting method should be acknowledged both for mechanical and marketing point of view. From mechanical point of view, engineer should take HAZ into account while designing the part since edges have been affected and part will not meet the expectations. Managers should also know this information as it is essential for them to advise customers and maintain brand image.

Closest research that has been made and published in worldwide web is done by Federal Highway Administration of U.S. Department of Transportation [14]. Research was carried out to find out about HAZ in structural steel after oxy-fuel gas cutting. Although only one cutting method was used, achieved results could be similar to other thermal cutting methods like laser or plasma cutting. Expected difference would be width of heat affected zone since different thermal cutting methods put different amounts of energy into the blank. This is due to different cutting temperature and speed. This results as different heat input into blank, thus different HAZ [14,15].

During cut, edge is effected and internal structure starts to change. High temperature cutting melts the material and flows out but the energy given from cutting source spreads in both ways (Figure 2.**9.** ) and transforms material. Temperature softens it as internal structure is changed and grain size is increased. Width of heat affected zone, in which steel is softened is directly linked to two main factors: cutting temperature or power and speed. Both factors are linked together since manufacturers of cutting machines make various researches to find maximum speed of minimal power, but sufficient quality. It is clear that flame has to both melt the metal and remove it at the same time, which is the main reason of minimum cutting speed [14].




(a) Top View.

(b) Cross-section.

Figure 2.9. Material change during thermal cutting [13]

Cross section of cut edge shows various steel structures (Figure 2.10). Martensite forms in top layers as it receives a lot of heat during cut, but also auxiliary gas rapidly cool this layer. But it is well known, that structural steel like S235 or S355 does not have enough of carbon in its chemical composition to be hardened. As material is molten in cutting area, and the sides have high temperature, carbon, which is released from molten metal is able to flow to the sides thus carbonizing edges. Of course, diffusion distance is really low, but still edge is affected [14;15].

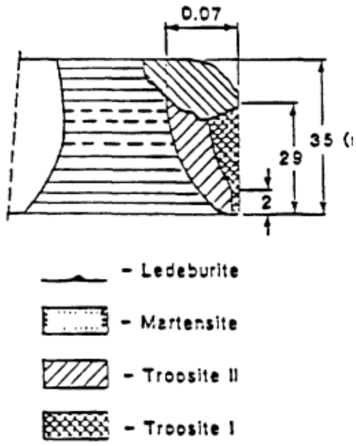



Figure 2.10. Cross section of cut edge with representation of areas in which steel structure has been changed [13]

Heat affected zone study reveals how the hardness of material changes from cutting edge and this material is useful to know while processing steel. Same results could also be applied to steel Hardox as it is cut with heat-treatment already achieved and further heat input, especially when it exceeds 250°, C will only damage its internal structure and decrease its hardness. Width of heat affected zone is useful to know when engineer has to know additional allowance for further machining like milling of part to reach certain part dimensional tolerances.

## 1.5.Real-life applications of steel Hardox

Steel manufacturer SSAB distinguishes 4 main application areas [23]:

1) Recycling (figure 2.11)
2) Roadbuilding (figure 2.12)
3) Quarries (figure 2.13)
4) Mining (figure 2.14)

Each application field is furtherly described as what parts may be manufactured from this wear-resistant steel.

Figure 2.11. Hardox steel application in recycling equipment

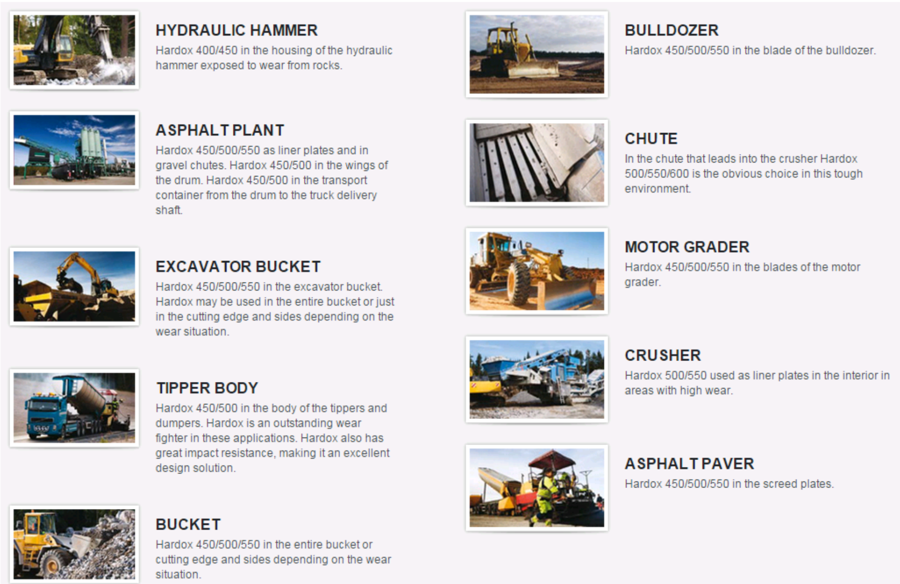



Figure 2.12. Hardox steel application in roadbuilding equipment

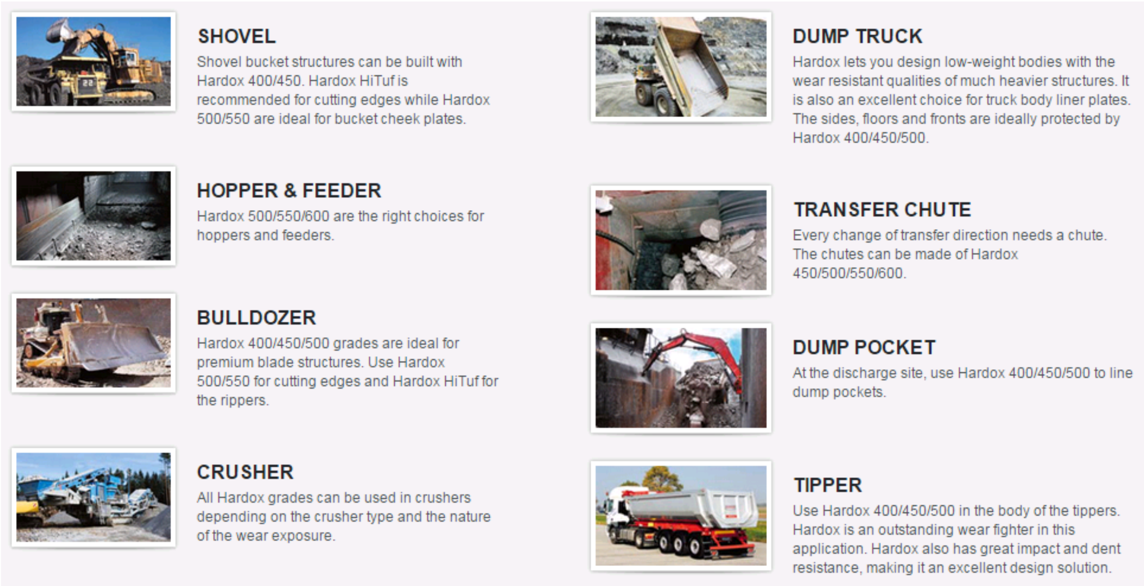



Figure 2.13. Hardox steel application in quarrying equipment

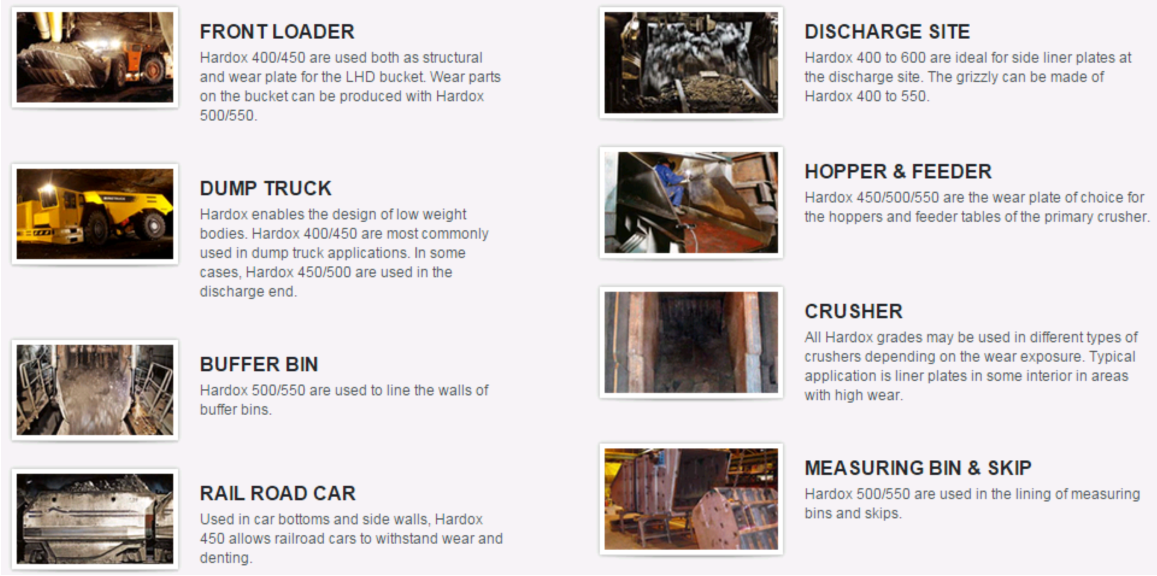



Figure 2.14. Hardox steel application in mining equipment

Of course, different areas of applications may be researched. One of those areas might be farming equipment, where various components, prone to wear may be produced from this steel [24]. One of the simplest examples may be hammer for centrifugal grain hammer mill (Figure 2.15 and figure 2.16)

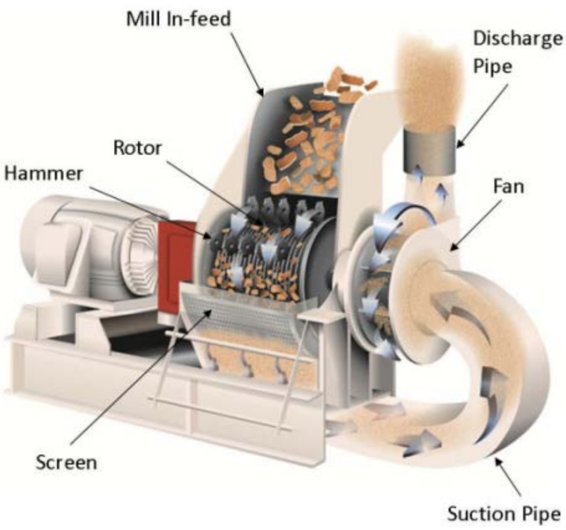



Figure 2.15. Grain hammer mill [24]

Figure 2.16. Grain hammer mill hammer example [25]

Such hammers are manufactured in small batches (up to 300 pcs. per month) and sold locally as spare parts or together with new equipment.

Also, parts like mill screens also might be produced from Hardox steel, since they often suffer from abrasive wear.

# 2. EQUIPMENT AND METHODS FOR RESEARCH

## 2.1.Methods and techniques

Research begins by preparing specimens, cut from sheet material using different cutting methods: Laser, Plasma, Oxy-fuel Gas, Water jet.

Technical features are listed below [20]:

Technical features of laser ByAutonom 3015 6.0 kW (Figure 3.1.):

- Sheet cutting range: 3048 × 1524 mm (two changeable tables);
- Maximum sheet thickness: 25 mm (steel), 25 mm (stainless steel), 15 mm (aluminium)
- Positioning speed simultaneous: 169 m/min;
- Acceleration: 30 $m/s^2$;
- Positioning accuracy: +/- 0.1 mm/m;
- Repeatability: +/- 0.05 mm/m.
- Edge detection accuracy: +/- 0.5 mm

Figure 3.1. ByStronic (Sweden) ByAutonom 3015 laser [22]

Technical features of fiber laser BySprint 3015 3.0 kW Fiber (Figure 3.2.):

- Sheet cutting range: 3048 × 1524 mm (two changeable tables);
- Maximum sheet thickness: 20 mm (steel), 12 mm (stainless steel), 12 mm (aluminium), 6 mm (brass, copper)
- Positioning speed simultaneous: 140 m/min;
- Acceleration: 12 $m/s^2$;
- Positioning accuracy: +/- 0.1 mm/m;
- Repeatability: +/- 0.05 mm/m.
- Maximum efficiency: up to 4÷6 mm of thickness

Figure 3.2. ByStronic BySprint fiber laser [21]

Main technical data of plasma and gas cutting machine Cortina DS-3100 manufactured by Czech company MGM s.r.o. (Figure 3.3.):

- Plasma source: Thermal Dynamics Pak Master 150XL;
- Maximum thickness of quality plasma cut: 20 mm (carbon non-alloy steel);
- Maximum dividing  plasma cut: 38 mm;
- Maximum thickness of gas cut: 230 mm;
- Positioning accuracy: +/- 0.1 mm;
- Table dimensions: 2500 × 13000 mm;
- Maximum cutting speed: 7.0 m/min;
- Achievable cut quality: in accordance with ISO 9013-2002 requirements.

Figure 3.3. Plasma and gas cutting machine Cortina DS-3100 (Czech republic) [21]

Technical data of ACM 3060 by Resato, the Netherlands (Figure 3.4.).

- Maximum pressure of water: 4130 bar;
- Number of cutting heads: 2;
- Possibility to cut at angle +/- 45 degrees
- Maximum workpiece dimensions: 3000 × 6000 mm;
- Maximum cut thickness: 200 mm;
- Cutting accuracy: +/- 0.1 mm/m;
- Repeatability and positioning: +/- 0.05 mm;
- Cutting speed: 1,0 ÷ 30000 mm/min;

- Acceleration: 500 mm/s².


Figure 3.4. Resato (Netherlands) ACM 3060 waterjet cutting machine [21]

### 2.1.1. Specimen preparation

After specimen has been cut (Figure 3.5) it has to be further prepared for testing. In order to see structure under microscope, specimen has to be polished and etched to contrast ferrite and carbon structures. For polishing machine sample has to be put into cylindrical holder. So part of the specimen has been cut at least 10x10mm in size, to ensure that HAZ will be visible. Downsizing was done by using water-abrasive jet cutting machine so to not put any heat into part and disorder results.

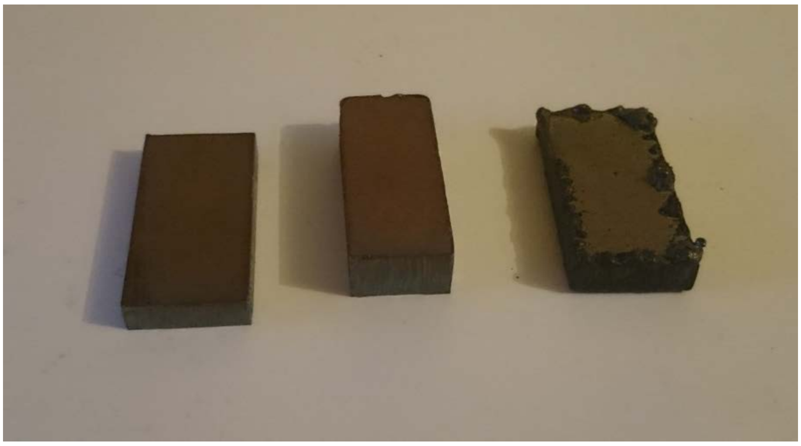


Figure 3.5. Samples cut by different methods

After downsizing specimen, bundle of them can be casted into holder, which in this case is small length of tube. Casting is useful as it keeps specimens in place, it is strong, cheap and doesn't damage samples. For this purpose, epoxy resin was used.

Next operation is polishing and etching. Polishing is made using special grinding and polishing machine (Figure 3.6.)

Figure 3.6. Polishing machine Smartlam 2.0

Technical data is listed below:

| | |
|---|---|
| Plate capacity | Ø 300 mm |
| Body | Steel, coated with epoxy paint |
| Bowl | Removable resin basin for easy cleaning |
| Controls | Color touch screen 3,5” to control the machine: start/stop speed and direction of the 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 |
| Motor | 0,75 kW |
| Voltage | 230 V – 50 Hz single-phase |
| Dimensions L x H x D | 450 x 300 x 650 mm |
| Weight | 30 kg |

Etching is made by rubbing strong acid onto specimen. After some time, acid must be rinsed off and specimen dried. Figure 3.7. shows finished specimens, ready for further analysis.

Figure 3.7. Polished and etched specimens in holder. Gap filling material is epoxy resin

Width of heat affected zone could be found in two ways:

1) Doing photos with microscope and measuring length of structure, that has been affected.
2) Doing microhardness research in order to find out varying hardness.

2nd method is by far more accurate as it also measures hardness at the specific point. Microhardness is also called Vickers hardness test since measuring principle is their creation. It is an alternative to Brinell's principle of hardness measuring. Test scheme ir shown at figure 3.8. Test is carried out as measuring of indentation, that is done by pressing diamond tipped prism into specimen with certain force. After measuring diagonals, distances are put into formulas and converted into hardness [6]. Machine to be used is Walter Uhl – VMH002 (Figure 3.9.). After measuring diagonal distances, machine calculates hardness, stores received data and create figures that can be exported and furtherly analyzed. Then specimen is moved by specific distance and whole measuring process is repeated.

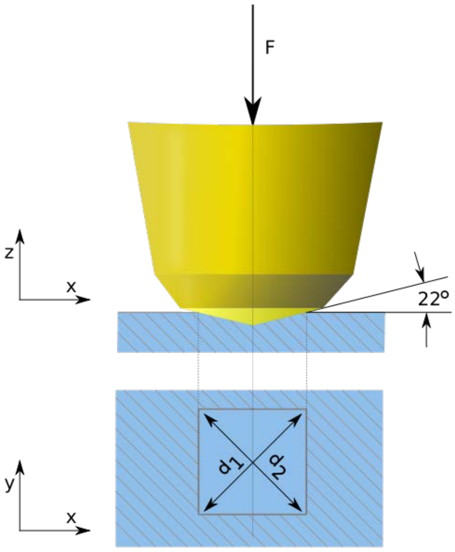



Figure 3.8. Vickers hardness by microindentation test scheme [19]


Figure 3.9. Microhardness measuring machine Walter-uhl VMH-002 [21]

Indentation is done with specific mass loaded on indentation tip. For this  research 200g mass will be used. Distance between indentations varies because width of HAZ depends on cutting method

After microindentation tests all specimen were photographed by using special microscope with digital camera (Figure 3.10.). Photos with different zooms will clearly show varying microstructure and impact of heat input. Microscope is equipped with 4 different objectives with zooms of : 2,5; 5; 20 and 50 times.

Figure 3.10. Microscope Zeiss AX10 with digital camera

# 3. RESEARCH OF HEAT AFFECTED ZONE AFTER CUTTING

## 3.1. Background

For purposeful analysis, it is most useful to get as many specimens as possible so blanks with different thicknesses and cutting methods have to be made. Final result should reveal graph of HAZ by different thicknesses, although same cutting technique. Another purpose of the graph would be to forecast HAZ of different thicknesses that would not be studied in this paper.

## 3.2. Raw materials and blanks

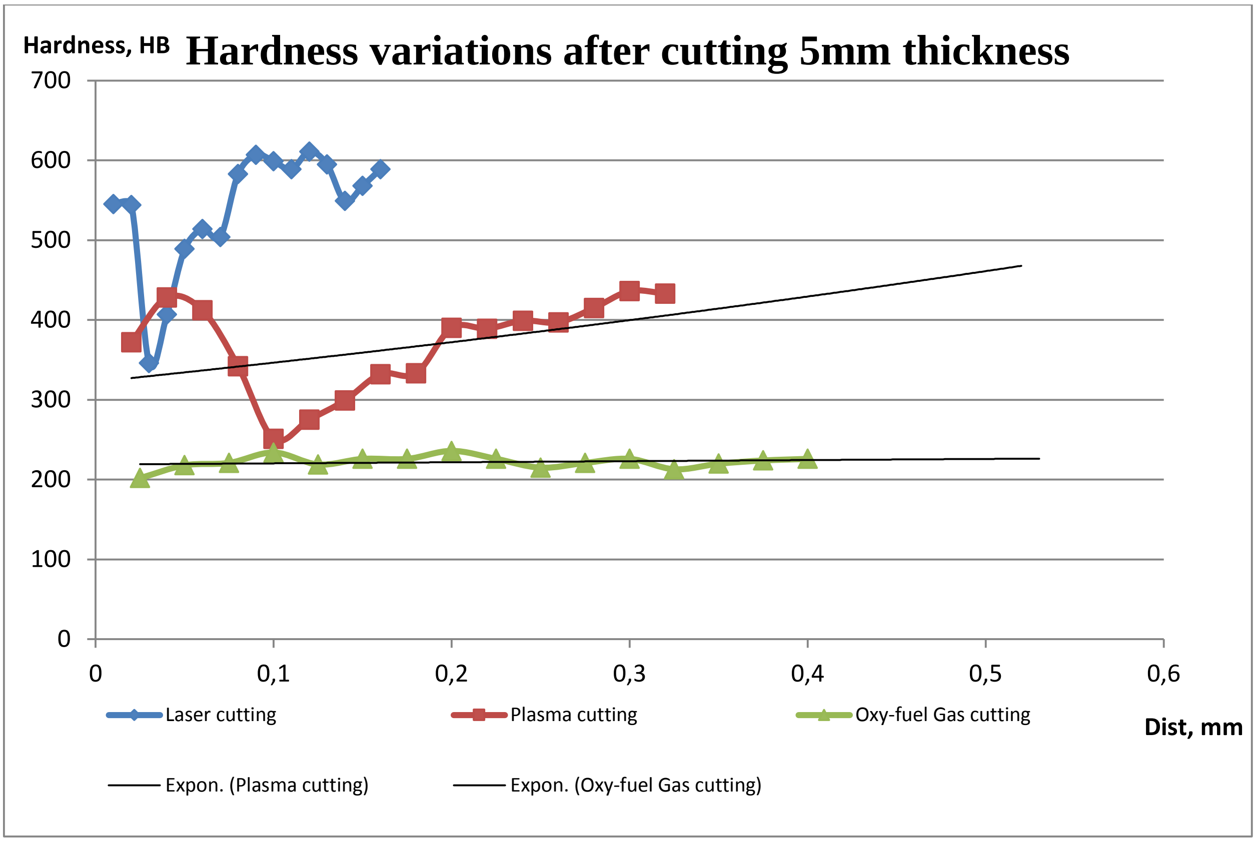
In order to get most accurate results, blanks for research should be of same size, therefore same possibilities to dissipate heat throughout blank. For this research, size of the blank would Tx20x40mm (T-thickness).

After cutting, blanks have to be numbered for further identification. Table 1 represents numbers of identification according to thickness of blank and method of cutting.

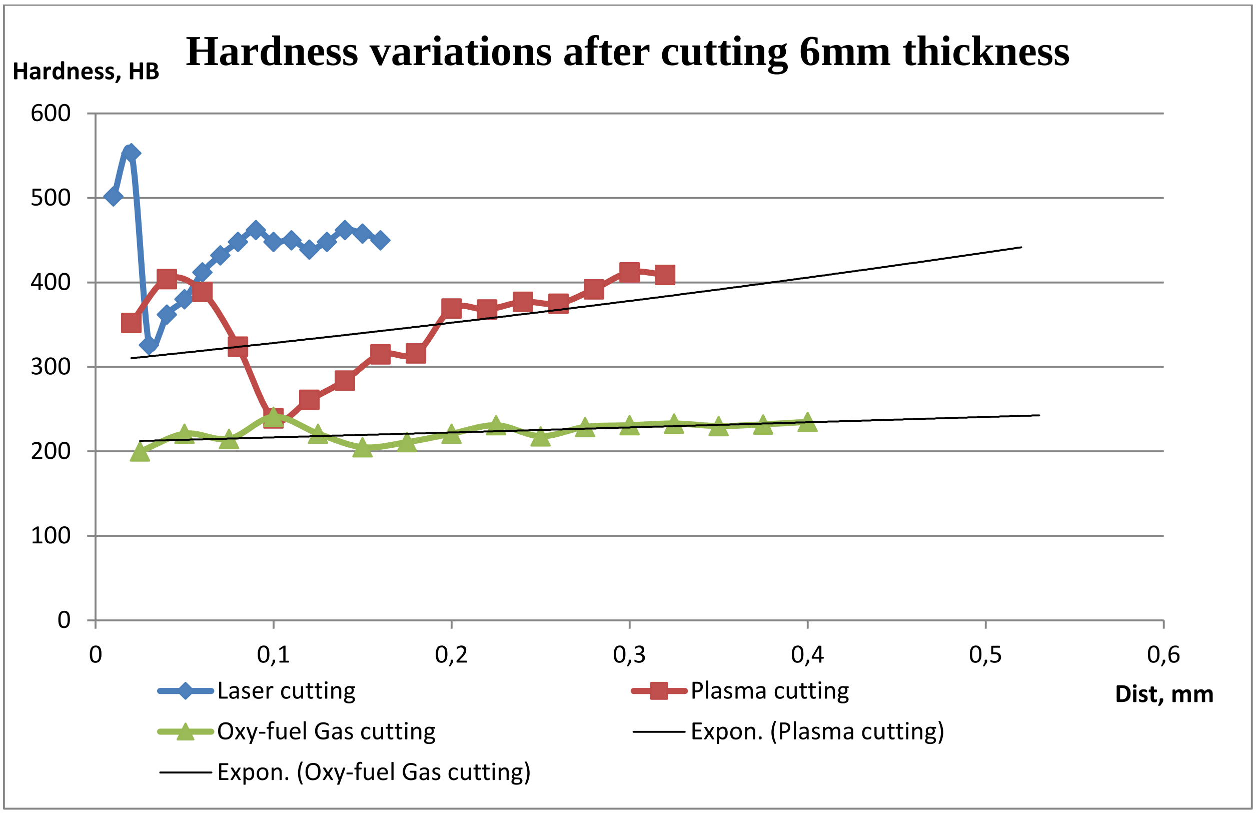
Table 3.1. Identification of specimens

| | **Specimen No.** | | | | |
|---|---|---|---|---|---|
| **Cutting Method** | 5mm | 6mm | 8mm | 10mm | 15mm |
| Laser | 7 | 10 | 12 | 14 | |
| Plasma | 6 | 9 | 4 | 3 | 1 |
| Oxy-fuel Gas | 5 | 8 | 11 | 13 | 2 |

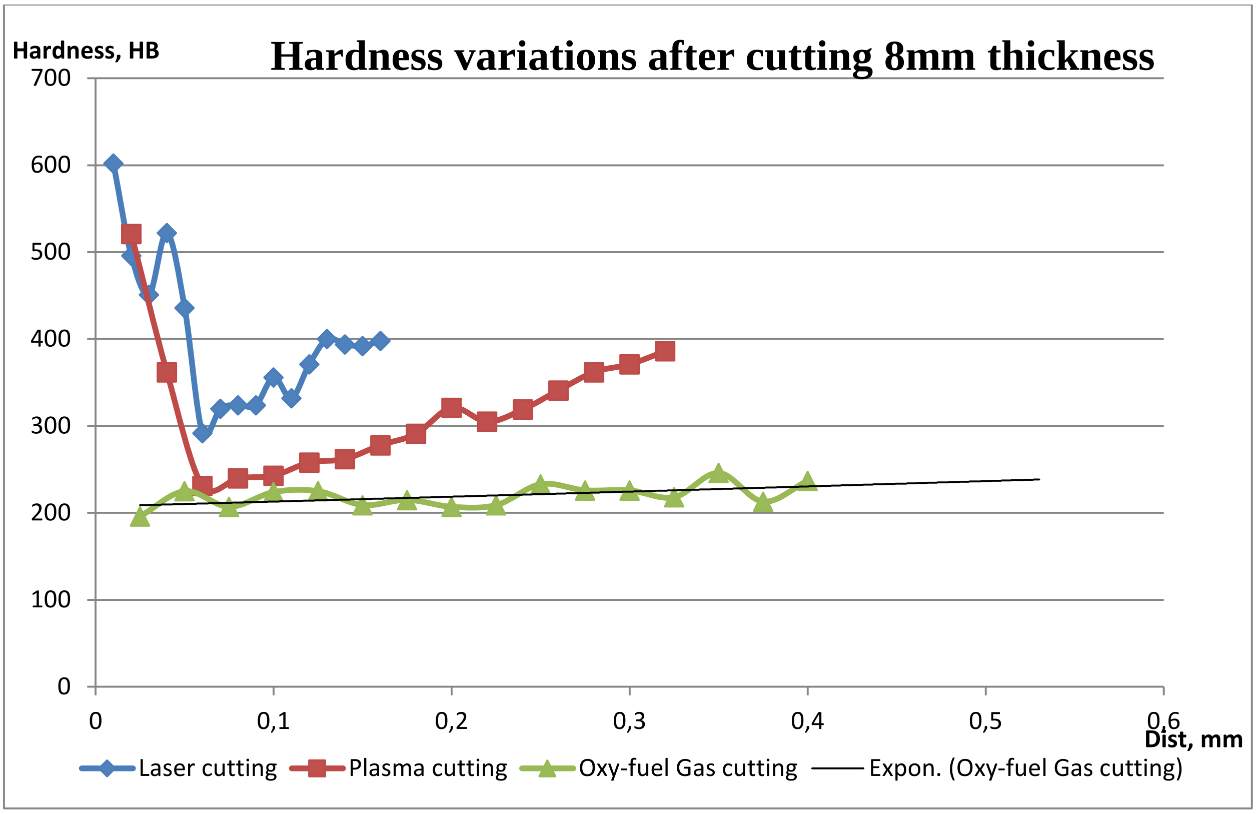
## 3.3.Results



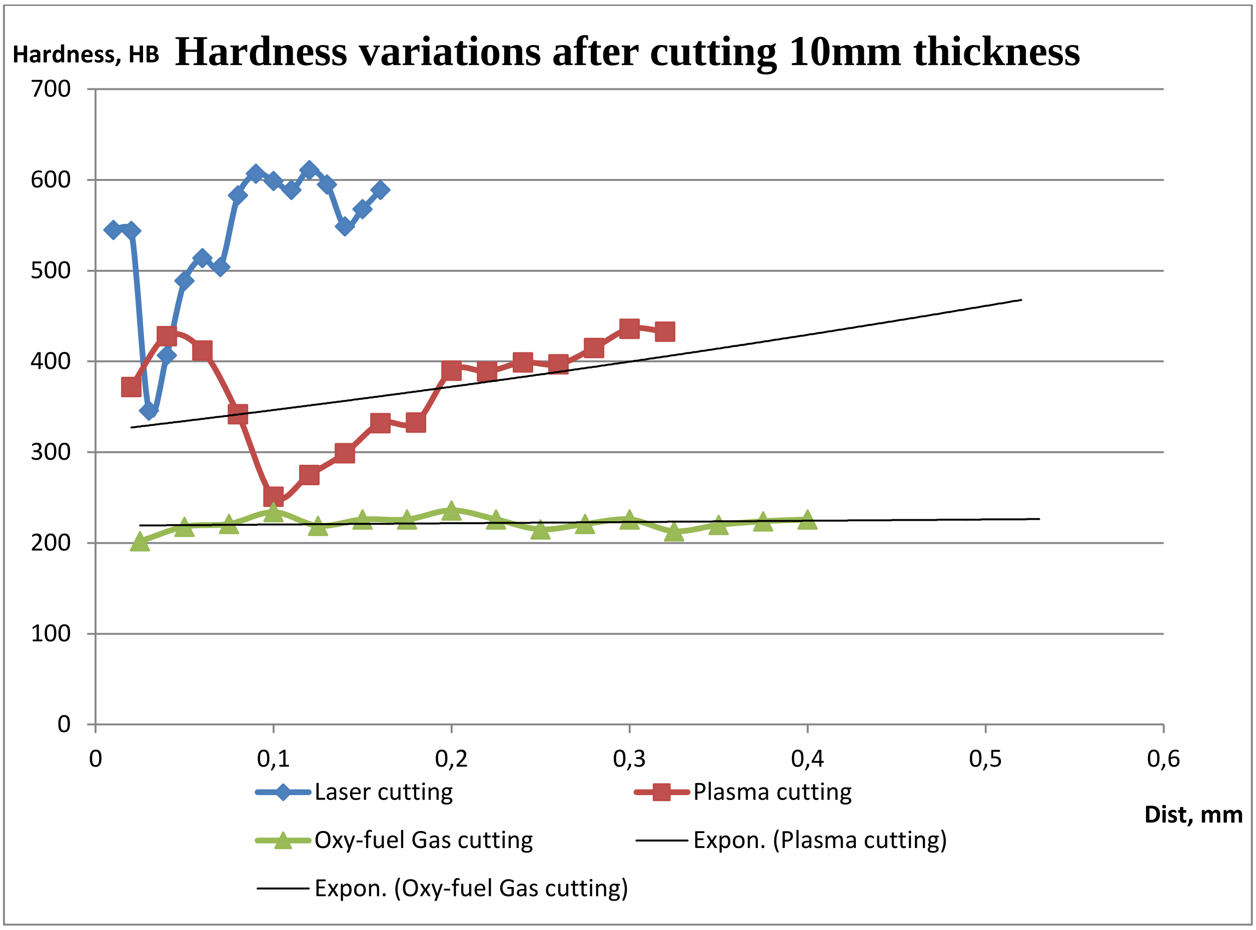

Graph.3.1



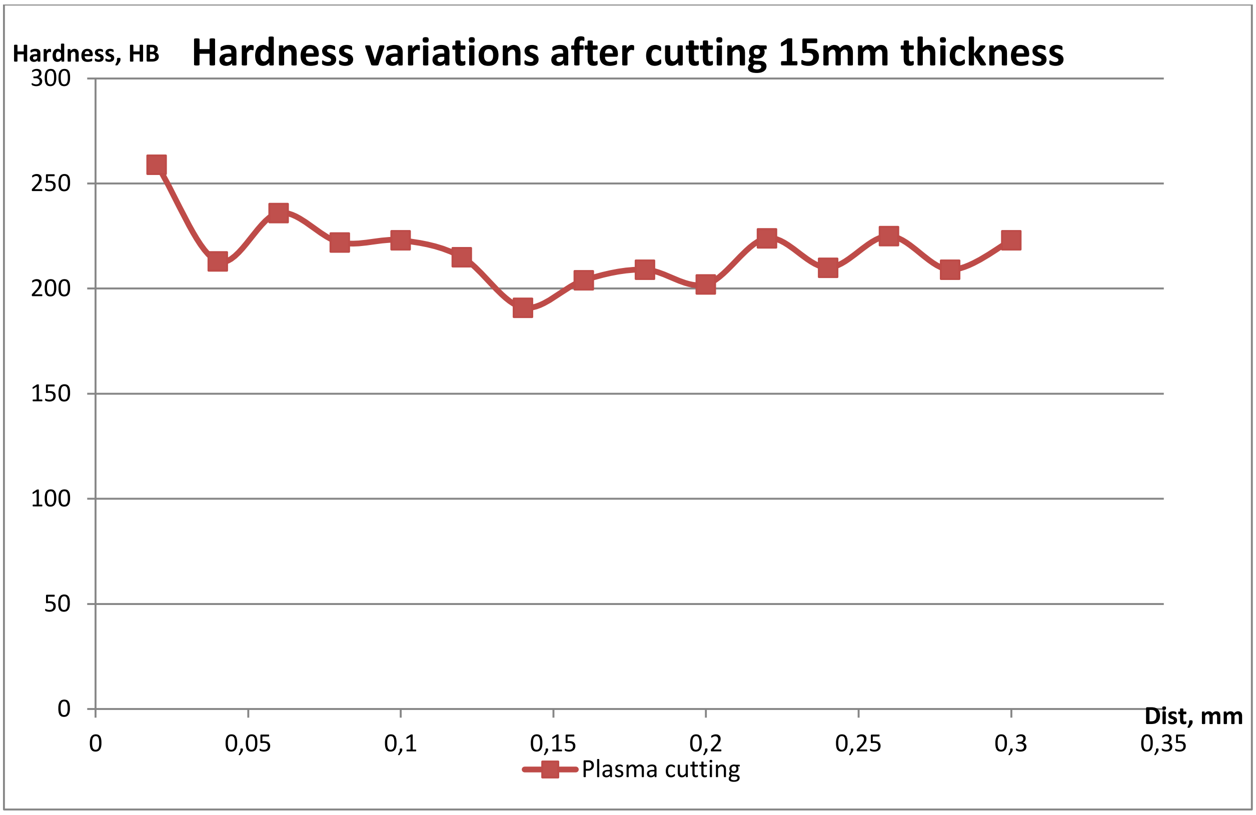

Graph 3.2.



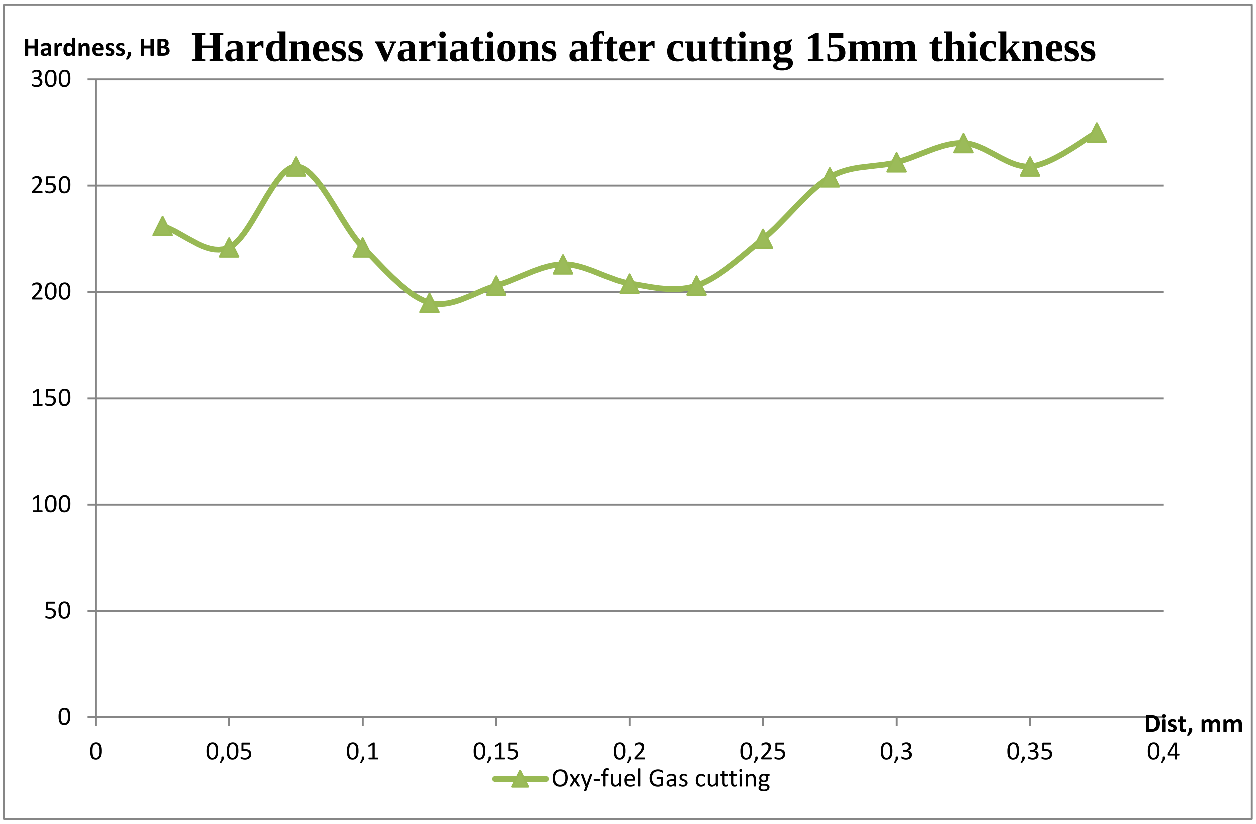

Graph 3.3.




Graph 3.4.




Graph 3.5.




Graph 3.6.

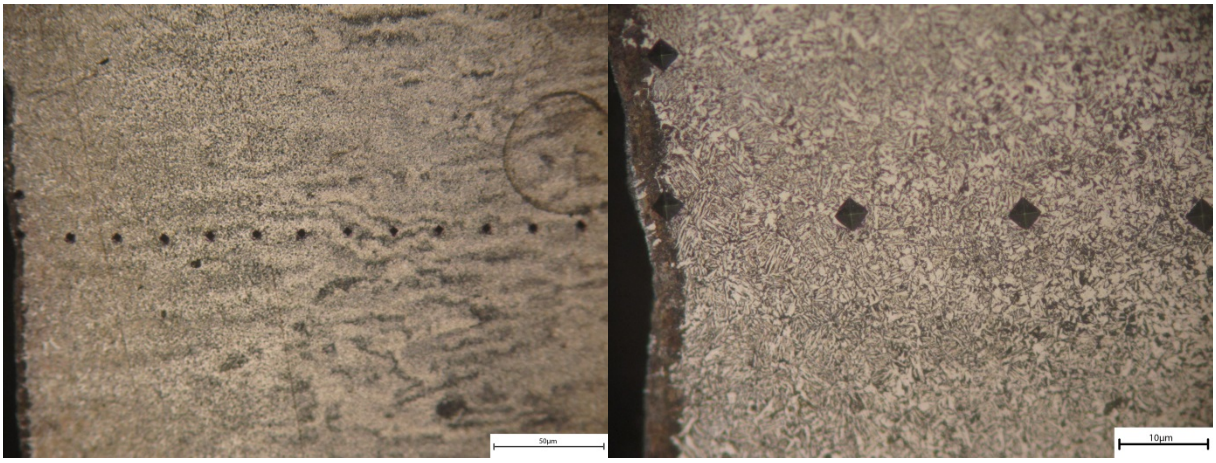


Figure 3.11. Specimen 1 (15mm thickness) zoomed views showing microstructure.

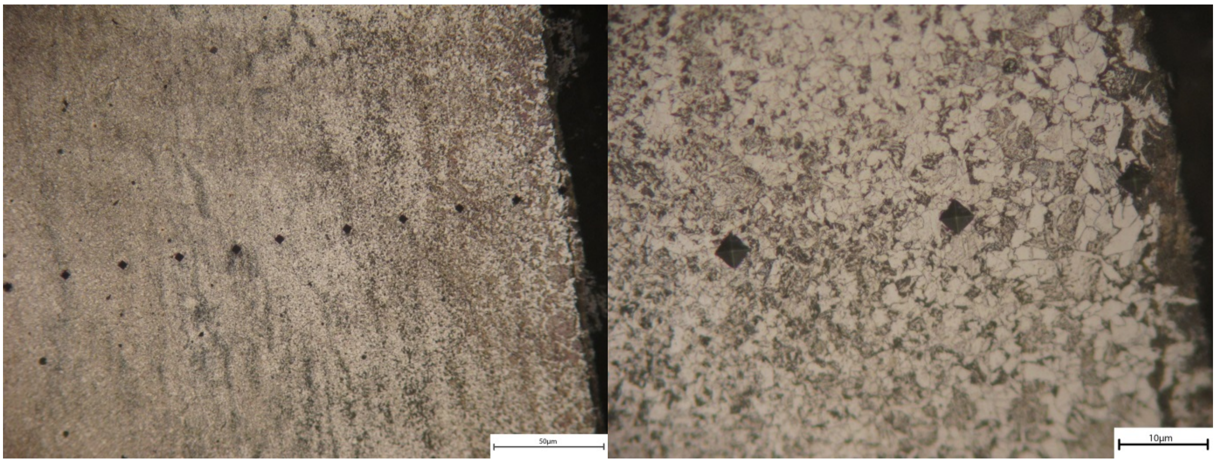


Figure 3.12. Specimen 2 (15mm thickness) zoomed views showing microstructure.

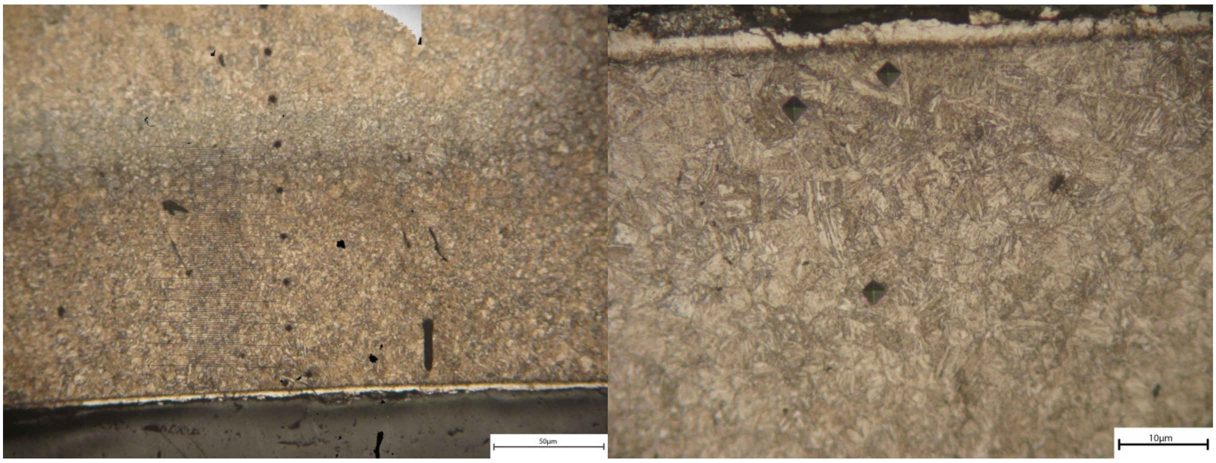


Figure 3.13. Specimen 3 (10mm thickness) zoomed views showing microstructure.

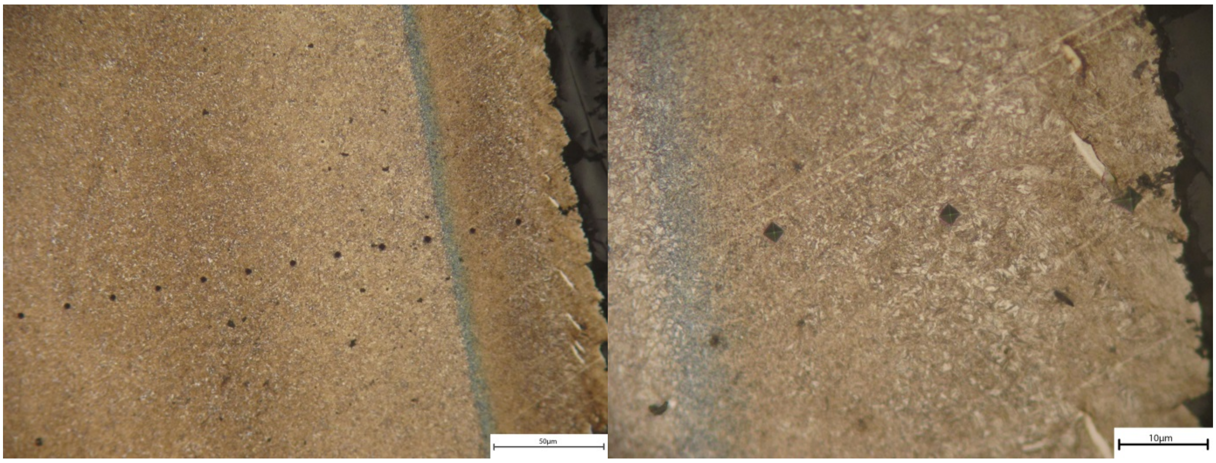



Figure 3.14. Specimen 4 (8mm thickness) zoomed views showing microstructure.

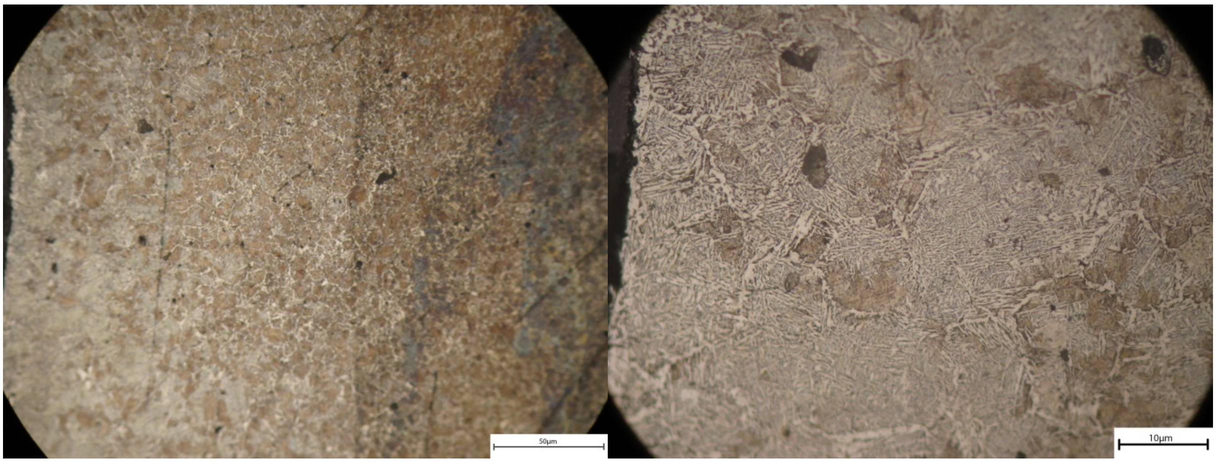



Figure 3.15. Specimen 5 (5mm thickness) zoomed views showing microstructure.

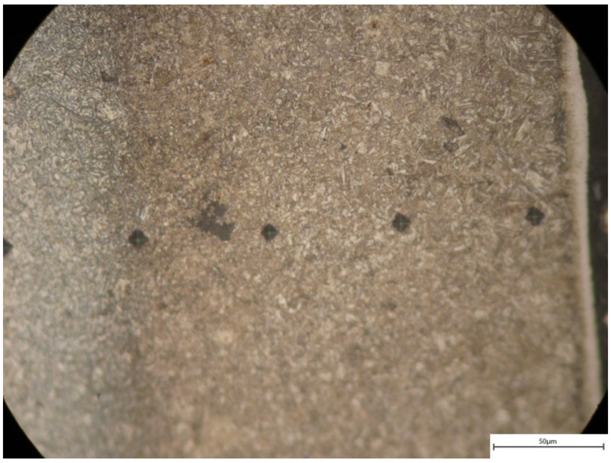



Figure 3.16. Specimen 6 (5mm thickness) zoomed views showing microstructure.

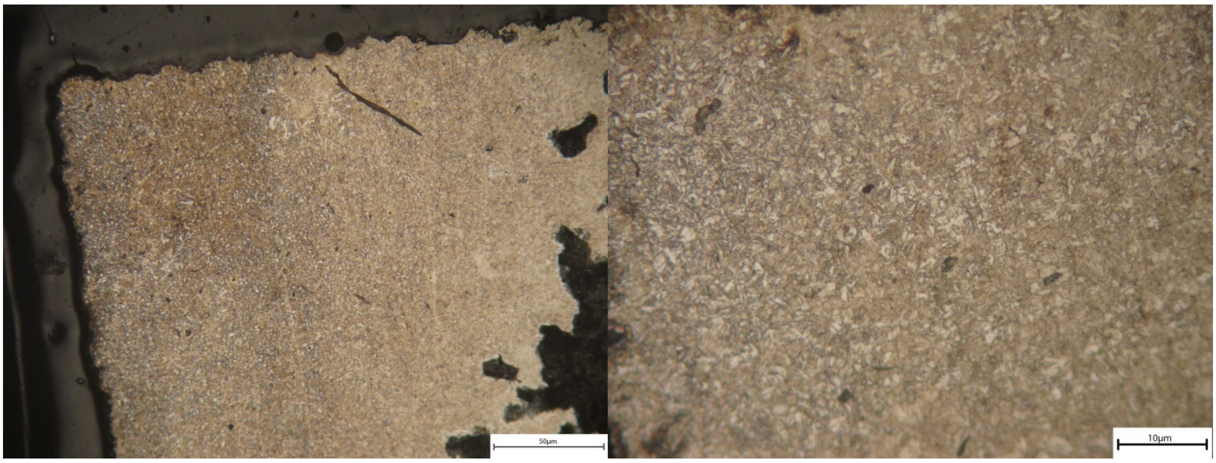


Figure 3.17. Specimen 7 (5mm thickness) zoomed views showing microstructure.

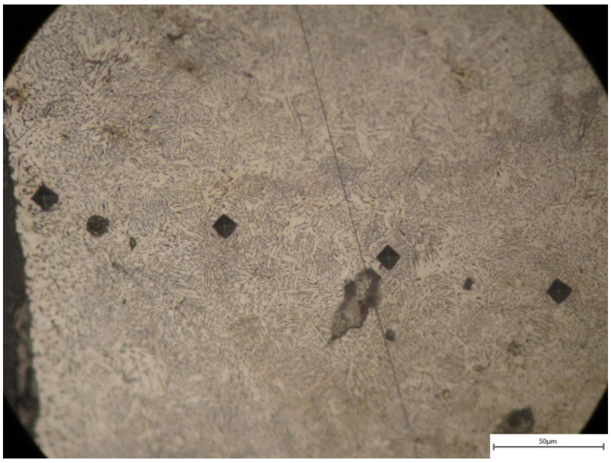


Figure 3.18. Specimen 8 (6mm thickness) zoomed views showing microstructure.

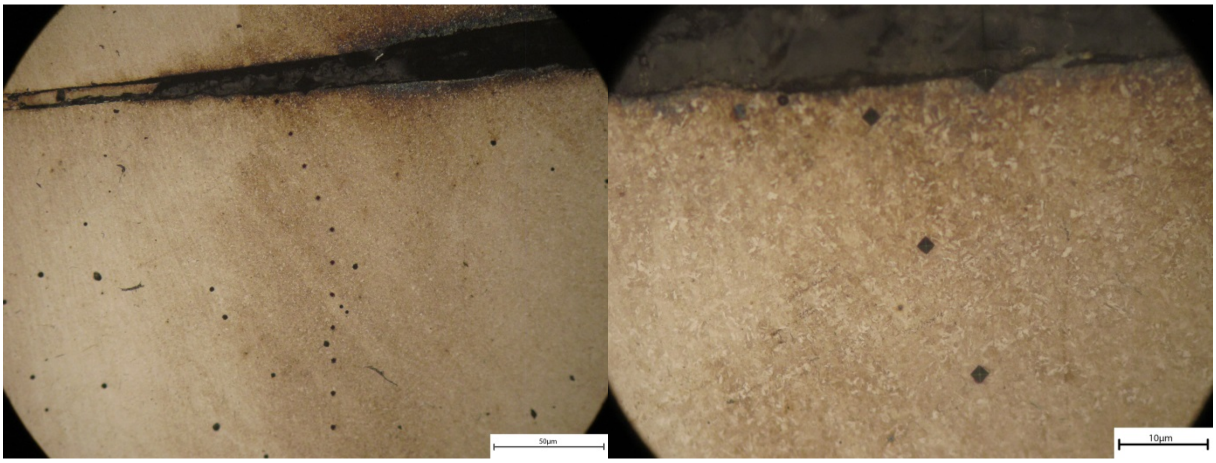


Figure 3.19. Specimen 9 (6mm thickness) zoomed views showing microstructure.

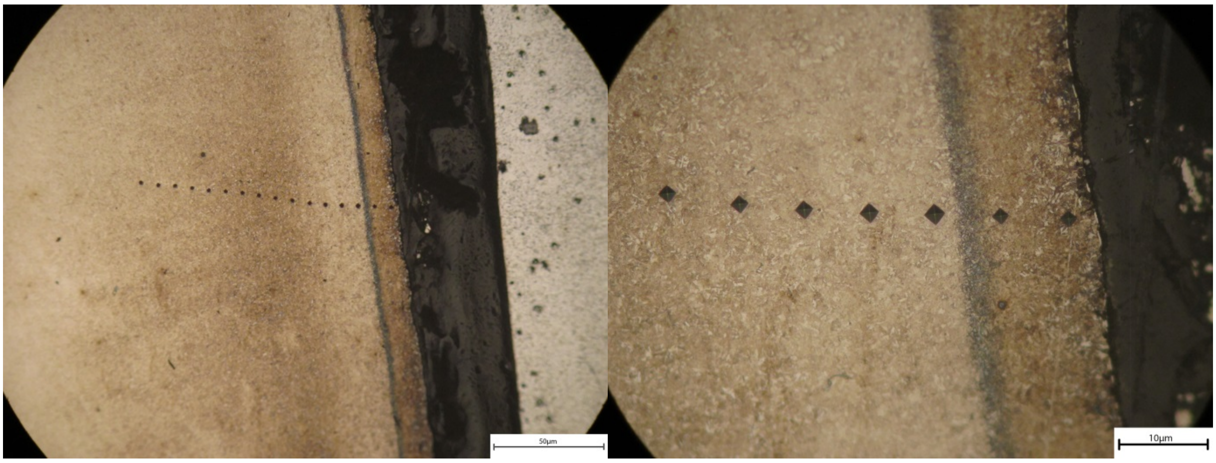



Figure 3.20. Specimen 10 (6mm thickness) zoomed views showing microstructure.

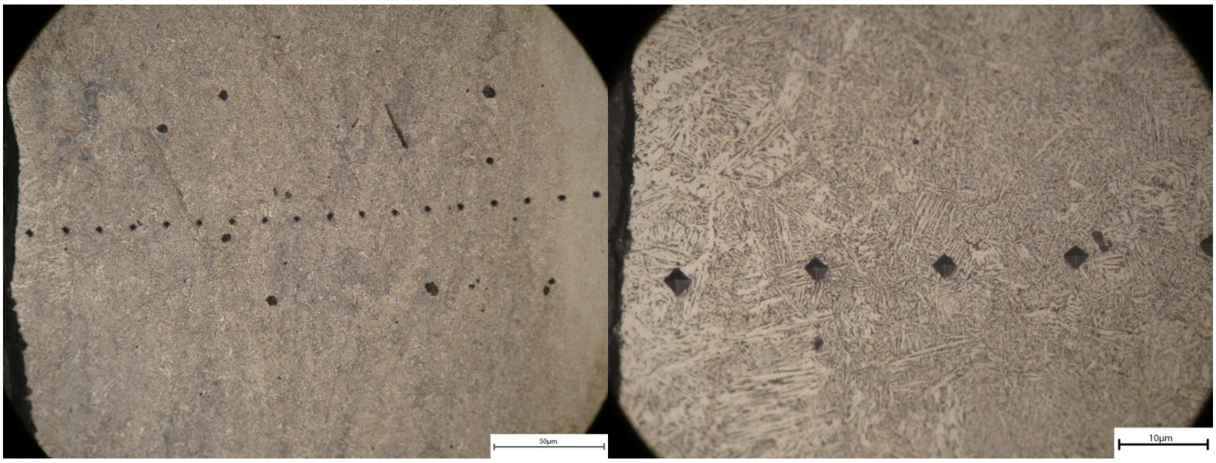



Figure 3.21. Specimen 11 (8mm thickness) zoomed views showing microstructure.

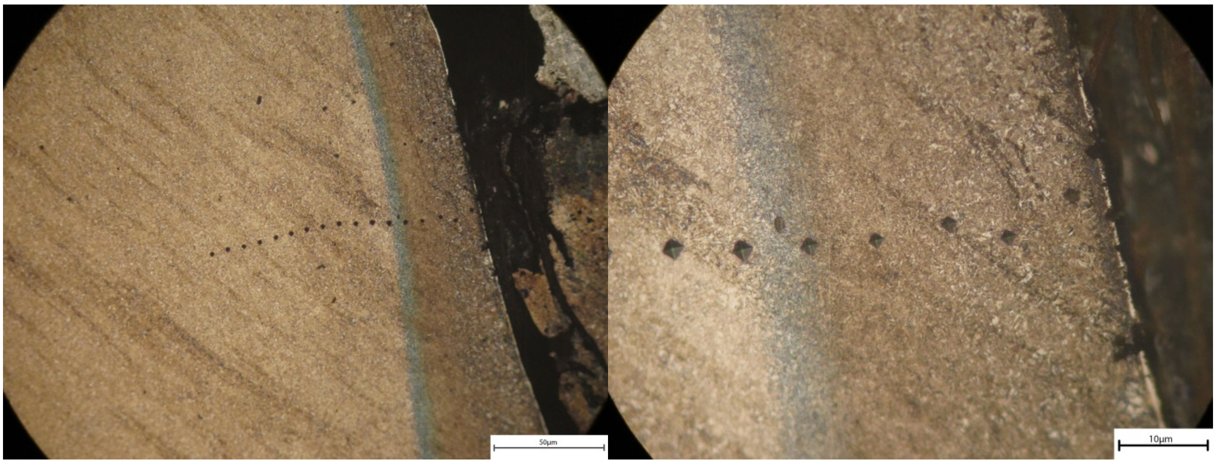



Figure 3.22. Specimen 12 (8mm thickness) zoomed views showing microstructure.

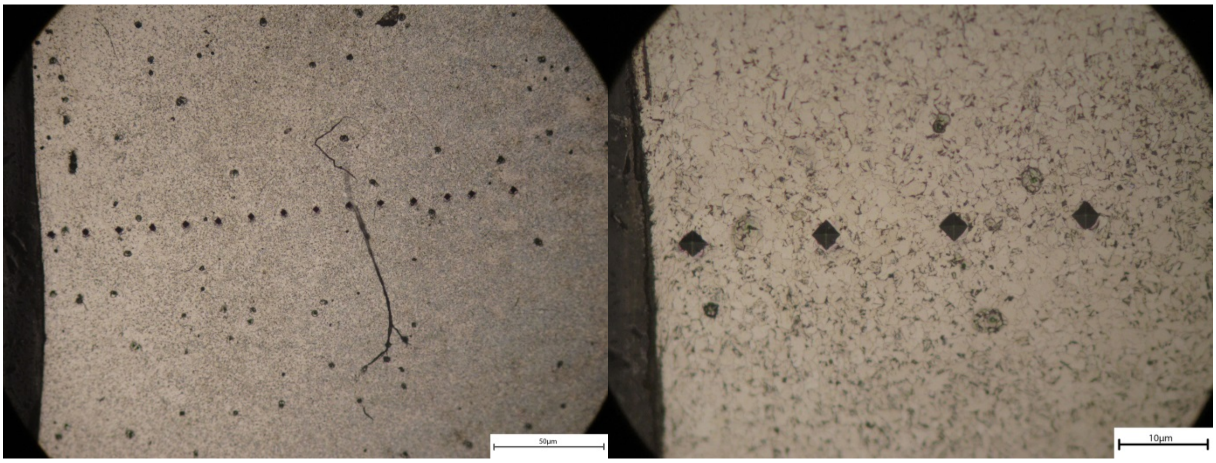



Figure 3.23. Specimen 13 (10mm thickness) zoomed views showing microstructure.

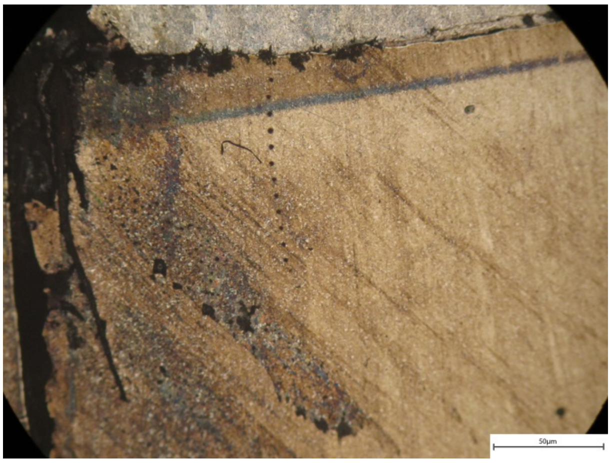
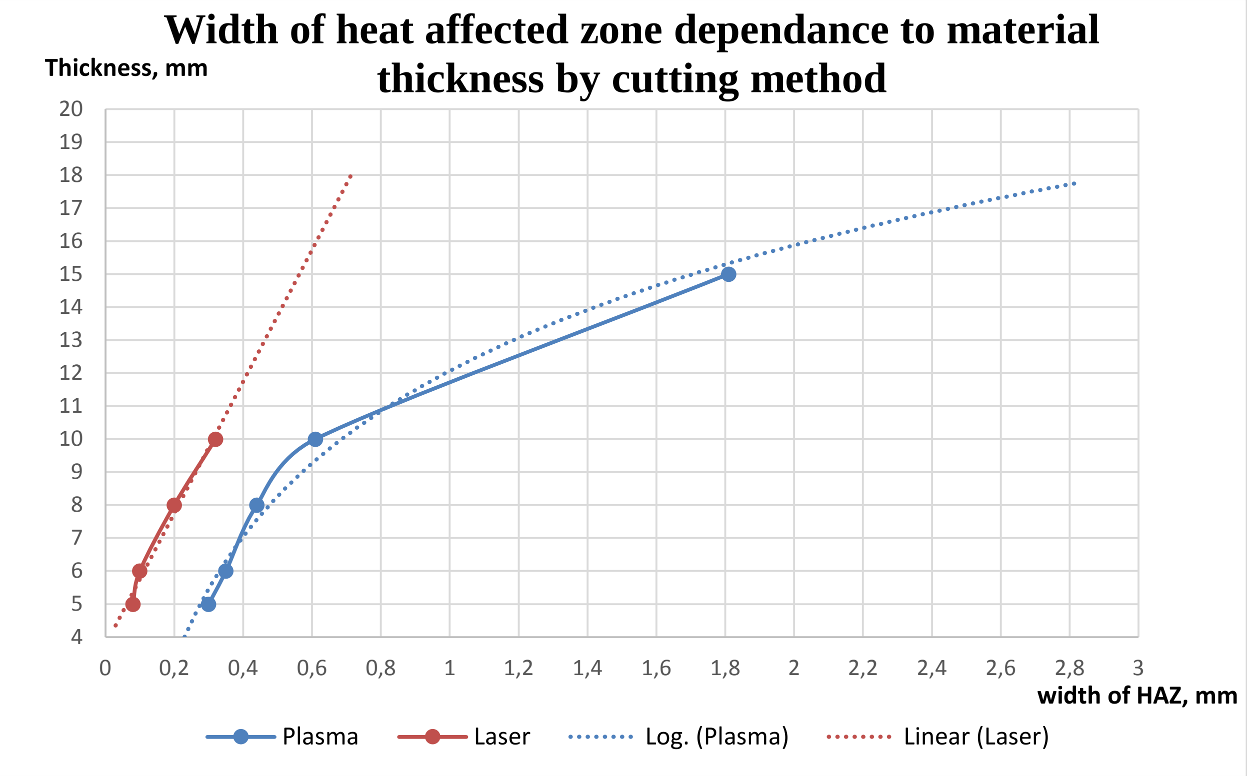
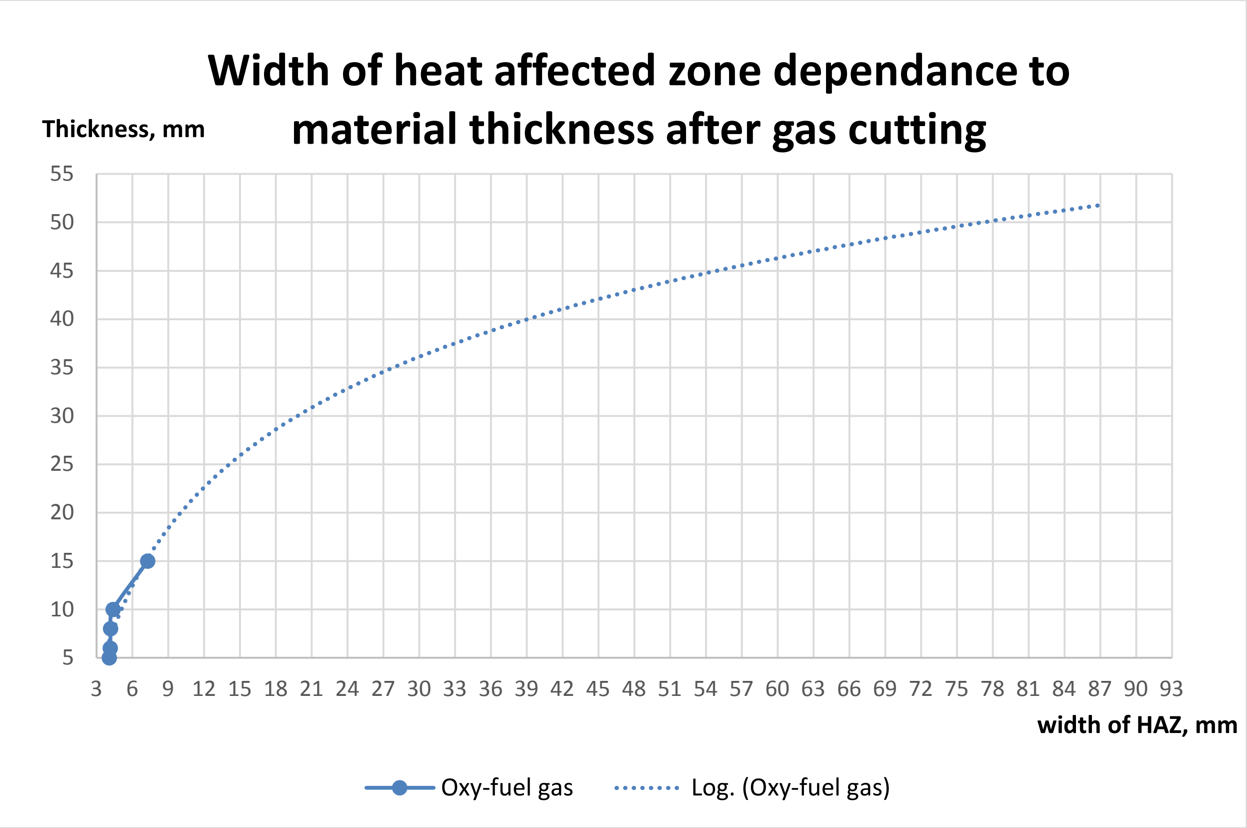



Figure 3.24. Specimen 14 (10mm thickness) zoomed views showing microstructure.




Graph 3.7.




Graph 3.8.

# 4. ECONOMICAL CALCULATIONS

## 4.1. Price comparison between different materials

All price calculations and comparisons below will be between structural steel (Grade S355; number 1.0037), carbon steel (Grade C60) and Hardox steel (Hardox 450).

First of all, price of material should be taken into consideration. Table 4.1. shows prices of materials. Prices of materials were acquired from Karbonas, JSC which is using these materials and maintains constant level of stock in house.

Table 4.1. Prices for different steel grades

| Material (Grade) | Price, €/1 kg |
|---|---|
| Structural steel (S355) | 0,75 |
| Carbon steel (C60) | 1,84 |
| Hardox steel (Hardox 450) | 2,10 |

## 4.2. Price comparison between different cutting methods

For calculations and comparisons, part is designed using 2D drafting software. Graphical sketch of part is shown in Figure 4.2. Technical drawing is attached in annex.

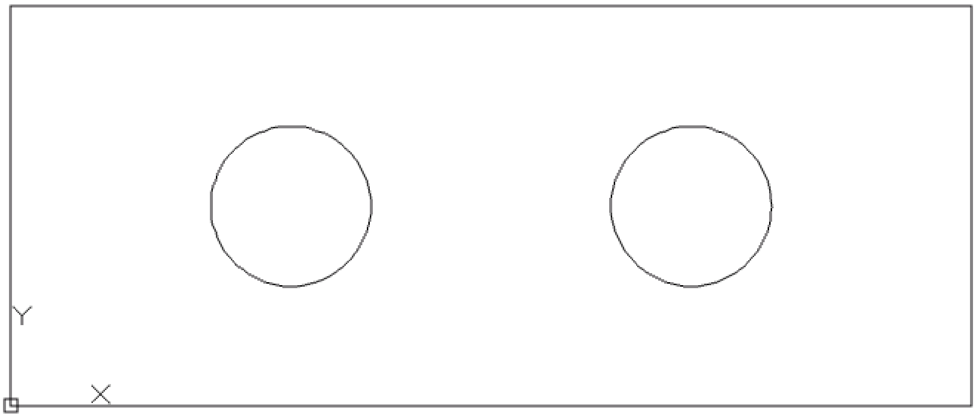



Figure 4.2. Sketch of part

Dimensions  of part:

Length – 120mm

Width – 50mm

Thickness – 15mm.

Last dimension is most problematic, as all of the mentioned cutting methods may be applied. For real-life price comparison, inquiry of 100 pcs. per order was sent to Karbonas JSC. It was asked to calculate part prices using two different materials – structural steel S355 and Hardox 450. Given price includes material, cutting and packaging prices and they are equal to current market prices. Prices from commercial offer are put in table 4.2.

Table 4.2. Part prices, calculated using different materials and cutting techniques

| **No.** | **Material** | **Cutting method** | **Material price, €/1pcs.** | **Cutting price, €/1pcs.** | **Part price, €/1pcs.** |
|---|---|---|---|---|---|
| 1 | S355 | Water-abrasive jet | 0,66 | 4,54 | 5,20 |
| 2 | S355 | Plasma | 0,73 | 1,76 | 2,49 |
| 3 | S355 | Gas | 0,73 | 3,18 | 3,91 |
| 4 | S355 | Laser | 0,73 | 1,16 | 1,89 |
| 5 | Hardox 450 | Water-abrasive jet | 1,87 | 5,89 | 7,76 |
| 6 | Hardox 450 | Plasma | 2,13 | 1,76 | 3,88 |
| 7 | Hardox 450 | Gas | 2,13 | 3,18 | 5,3 |
| 8 | Hardox 450 | Laser | 2,13 | 1,16 | 3,29 |

### 4.3. Cost of HAZ.

ROI (return on investment) is greatly dependent on design and manufacturing process of part if it can be considered as investment. Whether part will have lots of edges or holes which are designed to be only cut (like screens) will be greatly affected by HAZ and will not perform as intended. HAZ may be compared to simple structural steel in mechanical properties. So the worth of part is decreased. For the part to be economically successful, manufacturing process must be balanced between cost of production and part quality. Several manufacturing routes may be created, represented by Figure 4.1.

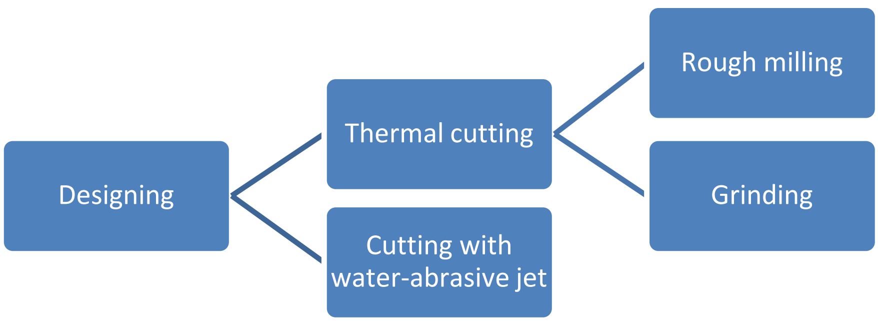



Figure 4.1. Manufacturing routes for Hardox steel

Shortest route is cutting with water-abrasive jet, which does not affect internal structure of steel and does not emit heat during cutting process, thus not creating any HAZ. Various cut edge qualities may be achieved, according to cutting speed and thickness of material. Since it is one of the slowest cutting methods, it is most expensive, but does not require additional manufacturing processes or cutting allowances.

Thermal cutting and further processing requires different approach. First of all, decision whether part will be further machined has to be made. If it is chosen, additional allowances must be added. Size of allowance is depended on cutting method and requirements for part.

Other possible production methods like stamping are eliminated. Hot stamping requires blank to be heated up to 900° C, which, in this case, will completely anneal steel. Cold stamping requires that material would be stamped before heat treatment. Stamps are made of strong durable steel, which is up 55 HRC in hardness. Since Hardox 450 is equal to about 44,5 HRC, stamp will wear out too quickly so price of part will be increased. This method is also discarded because Hardox is sold as already heat treated steel in sheet profile.

As the manufacturer suggests (Figure 2.2.) performance of Hardox steel, especially Hardox 450 compared to structural steel differs up to 4 times, but price is higher 2,8 times which means that for part to be economically useful part has to be less than 3 times expensive to have any payback.

Heat affected zone after cutting may be represented in graphic colors, showing width of annealed material. Width is based on graphs 3.7 and 3.8 from research results.

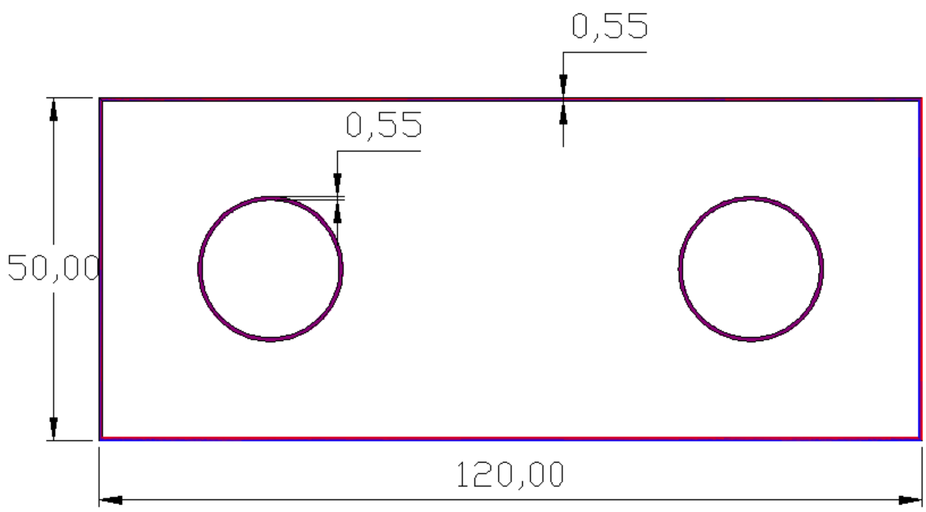



Figure 4.3. Graphical representation on HAZ after **laser** cutting.

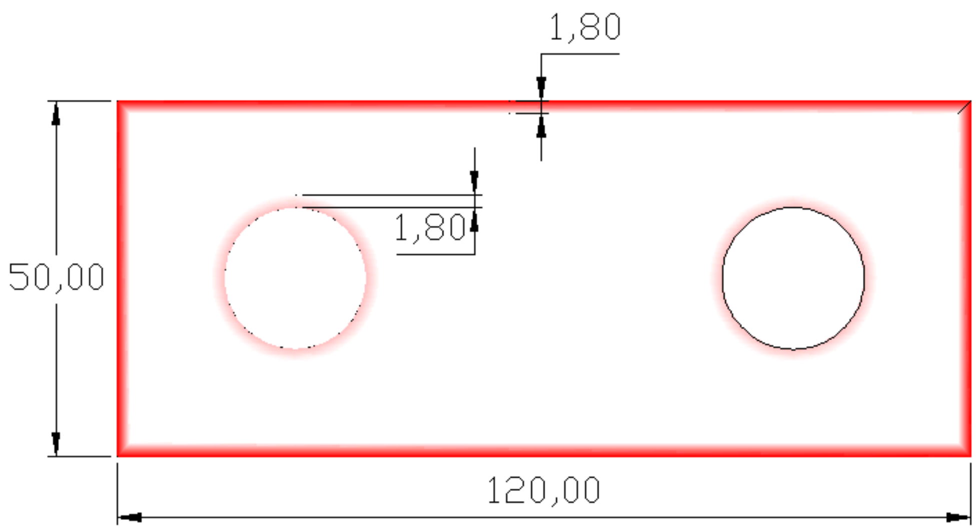



Figure 4.4. Graphical representation of HAZ after **plasma** cutting

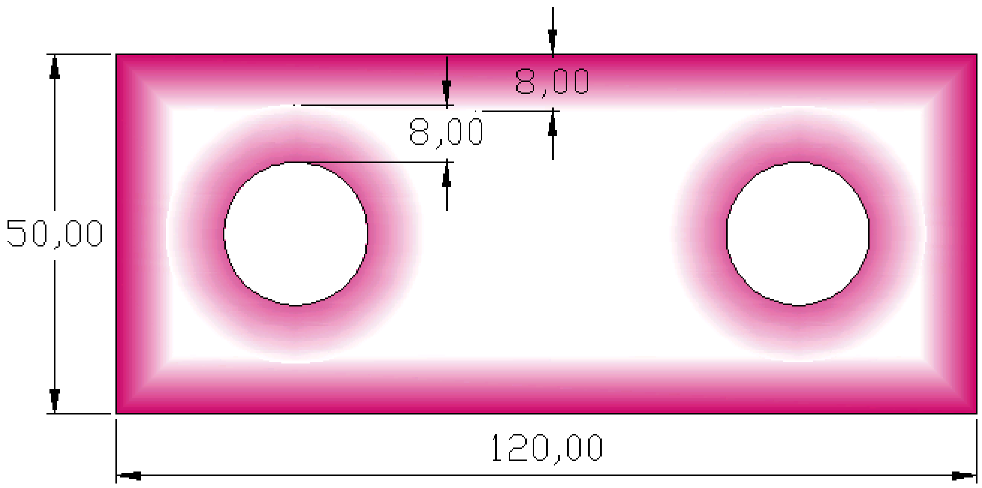



Figure 4.5. Graphical representation of HAZ after **gas** cutting

With this graphical representation, it is easy to see which thermal cutting leaves smallest areas that had been affected by heat. It could be basis for redesigning of part or selecting optimized manufacturing route.

Economical worth may be represented as area (in percentage) that has not been affected by heat. For analyzed part, this area is calculated and written to table 4.3. As the material anneals, due to heat inputs while cutting, it loses its hardness, therefore main mechanical property for this type of steel. Graphs from previous chapter shows that hardness drops to 200-300 HB, which is below designated hardness and part will not perform under wear conditions like it is intended. Since price of part is known, price of HAZ might be calculated like this:

Cost of HAZ = HAZ area, % * price of part

Table 4.3.Evaluation of HAZ

| Cutting method | Width of HAZ, mm | HAZ area, % | Cost of HAZ, € |
|---|---|---|---|
| Water – abrasive jet | 0 | 0 | 0 |
| Laser | 0.55 | 4.78 | 0,16 |
| Plasma | 1.8 | 15.74 | 0,61 |
| Gas | 8 | 71.19 | 3,77 |

For the calculation of total price, cost of HAZ should be added. This is for the material that will be lost faster and could be counted as an additional amortization. Simple equation can be generated and use for other parts as well. As the mechanical properties of structural steel do not change so significantly, it is not necessary to add cost of HAZ to part price. Therefore, this calculation is useful only to the materials that are liable to heat and can change hardness or other mechanical properties. Results for the analyzed part are put into table 4.4.

Total price = part price + cost of HAZ

Table 4.4. Total price of part (including evaluated HAZ)

| Cutting method | Part price, €/1pcs. | Cost of HAZ, €/1pcs. | Total price, €/1pcs. |
|---|---|---|---|
| Water-abrasive jet | 7,76 | 0 | 7,76 |
| Plasma | 3,88 | 0,61 | 4,49 |
| Gas | 5,3 | 3,77 | 9,07 |
| Laser | 3,29 | 0,16 | 3,45 |

Then prices can be compared to see what is the difference, especially in percentage to better understand which cutting method should be applied. This information is put into table 4.5.

Table 4.5. Price difference between different steel grades and cutting techniques

| Cutting method | Part price, €/1pcs. (S355) | Part price, €/1pcs. (Hardox 450) | Price difference, % |
|---|---|---|---|
| Water-abrasive jet | 5,20 | 7,76 | 49,62 |
| Plasma | 2,49 | 4,49 | 80,32 |
| Gas | 3,91 | 9,07 | 131,97 |
| Laser | 1,89 | 3,45 | 82,54 |

To see whether it is economical to create parts from Hardox steel, rather than structural steel, lifespan of part should also be taken into consideration. As the producer of hardox steel suggests, lifespan should be 1.1-4.0 times longer compared to structural steel (Figure 2.2) depending on Hardox steel grade. As the lifespan of Hardox 450 is up to 1.7, it is only economical to buy parts that are only up to 70% more expensive, so, in this case, that only leaves water-abrasive jet cutting.

Of course, other aspect should also be considered. If parts hold longer, that means that machinery has to be stopped less often to change the parts that have worn out. Less stops mean more working hours, therefore more income can be generated by machinery.

Such economical assessment can be applied to all kinds of parts. Procedure and steps for correct assessment should be same, although final judgement and decision should include other aspects, important to designer.

## CONCLUSIONS

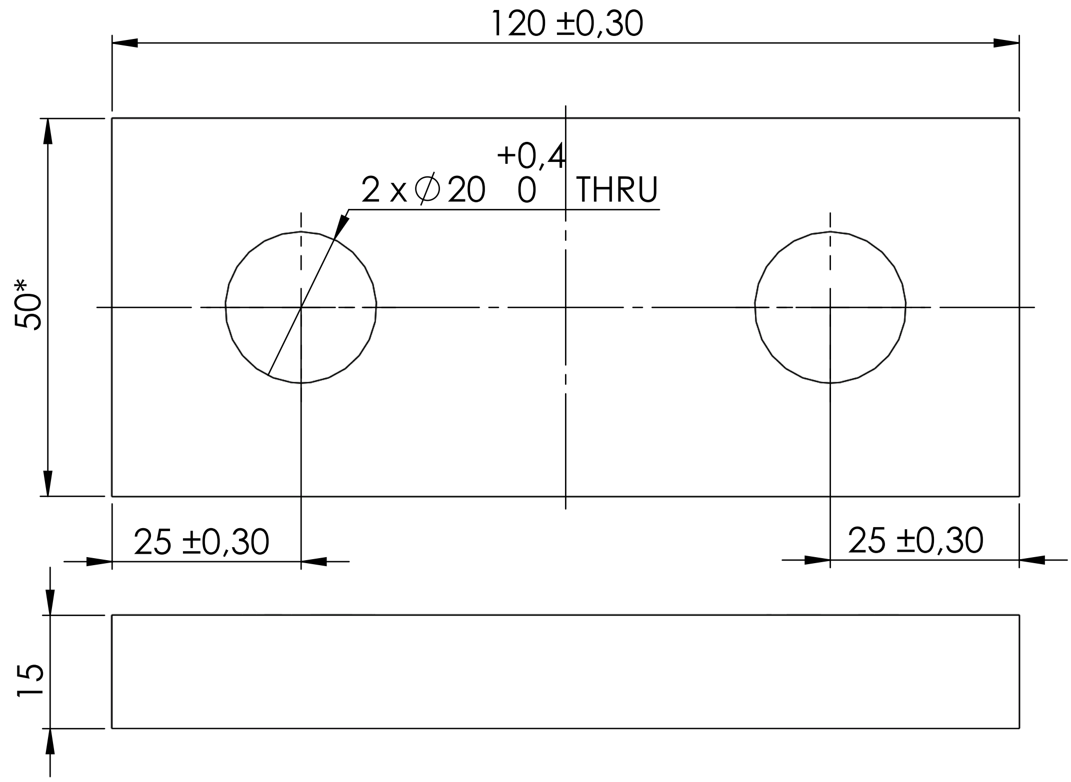
1. Hardox steel can be cut into blanks or parts using following cutting techniques:
   1.1. Water – abrasive jet
   1.2. Plasma
   1.3. Gas
   1.4. Laser
2. Hardox steel has a wide range of application fields including recycling plants, parts for roadbuilding, mining equipment.
3. Similar heat affected zone analysis, made by Federal Highway Administration of U.S. Department of Transportation show how hardness is changed from cut edge. Due to carbon infusion from melting material, edge is hardened.
4. Width of heat affected zone after cutting depends on thickness and cutting method. For thicknesses 5-15 they are:
   4.1. For water – abrasive jet cutting – 0mm
   4.2. For plasma cutting – 0,3 – 1,8mm
   4.3. For gas cutting – 4 – 8mm
   4.4. For laser cutting – 0,08 – 0,32mm
5. For other thicknesses, width of HAZ can be forecasted.
6. HAZ is a loss of material (material is softer in that area and will not perform as intended) and should be added to a price of part.
7. For the part to be economically beneficial, its price should be higher than relative service life interval, given by manufacturer.
8. Calculation method could be applied to other parts as well using same methods and approaches.

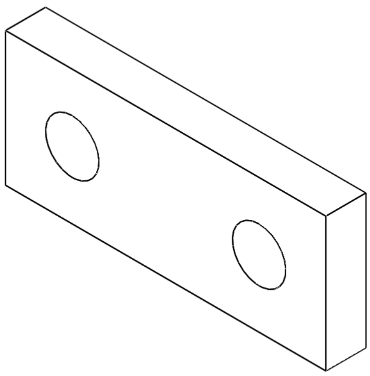
# REFERENCES


1. http://www.teskolaser.com/laserglossaryk.html
2. http://www.hardox.com/en/About-Hardox/Overview/
3. http://www.hardox.com/About-Hardox/Product-program/
4. S. Bočkus. Medžiagų inžinerija, I dalis. Technologija, 2013, 215 pages. Internet source (previewed 2014-04-14): https://www.ebooks.ktu.lt/eb/1129/medziagu-inzinerija-i-d/
5. P. Ambroza, L. Kavaliauskienė. Medžiagų sandaros ir savybių tyrimas. Technologija, 2012, 216 pages. Internet source (previewed 2014-04-14): https://www.ebooks.ktu.lt/eb/1129/medziagu-inzinerija-i-d/
6. P. Ambroza, L. Kavaliauskienė. Lydinių savybių keitimo terminiu poveikiu procesai ir technologijos. Technologija, 2011, 160 pages. Internet source (previewed 2014-04-14): https://www.ebooks.ktu.lt/eb/163/lydiniu-savybiu-keitimo-terminiu-poveikiu-procesai-ir-technologijos/
7. http://www.hardox.com/en/APPLICATIONS/Segments/#t-quarries
8. http://www.ssab.com/Global/Hardox/Brochures/en/016_TS_Hardox_Cutting_of_Hardox_wear_plate_UK.pdf
9. http://en.wiktionary.org/wiki/kerf
10. http://en.wikipedia.org/wiki/Water_jet_cutter
11. http://en.wikipedia.org/wiki/Laser_cutting
12. http://en.wikipedia.org/wiki/Plasma_cutting
13. http://www.hardox.com/en/Handling/Cutting1/
14. Federal Highway Administration of U.S. Department of Transportation. Heat-Affected Zone Studies of Thermally Cut Structural Steels. 1994. Internet source (Previewed 2014-05-23): http://ntl.bts.gov/lib/jpodocs/repts_te/7783.pdf
15. B. S. Yilbas. Laser cutting quality assessment and thermal efficiency analysis. Journal of Materials Processing Technology, 2004. Internet source (previewed 2014-05-23): http://www.worldlasers.com/articles/research/sdarticlej.pdf
16. D. Puskunigis, R. Jonušas. Metalų pjuvių gautų skirtinais pjovimo būdais kokybės tyrimas, 9-oji jaunųjų mokslininkų konferencija. Mechanikos inžinerija – 2010, Technologija.
17. Hardox steel grade program. Internet source (previewed 2014-10-17):

http://www.ssab.com/Global/Plate/Brochures/en/813_product_program_EN.pdf
18. Description of plasma cutting method. Internet source (previewed 2014-10-17). http://en.inforapid.org/index.php?search=Plasma%20cutting
19. Description of Vickers hardness test. Internet source (previewed 2014-11-05). http://en.wikipedia.org/wiki/Vickers_hardness_test
20. http://www.karbonas.eu/en/services/laser-cutting/
21. http://www.shelbourne.com/uploads/asset_image/2_516_e.jpg
22. https://www.google.lt/search?q=bystronic+fiber+laser&safe=off&espv=2&biw=1777&bih=861&source=lnms&tbm=isch&sa=X&ei=lWm1VNqOGMT9UIrMg5gH&ved=0CAYQ_AUoAQ&dpr=0.9#safe=off&tbm=isch&q=bystronic+byautonom+&imgdii=_&imgrc=8CIzEXKr2mFq-M%253A%3BGpqj3KkVoOixuM%3Bhttp%253A%252F%252Fwww.metal-interface.co.uk%252FPublic%252Fdata%252Fmarque%252Fproduit%252F16503%252FByAutonom.png%3Bhttp%253A%252F%252Fwww.metal-interface.co.uk%252Fcomparator%252Fcutting-punching%252F2d-laser_1.html%3B630%3B360
23. http://www.hardox.com/APPLICATIONS/Segments/
24. http://cdn2.hubspot.net/hub/23878/file-13477938-jpg/images/pneumatic_13.diagram-resized-600.jpg?t=1427463278670
25. http://g3hammers.com/product/double-ended-hammer-mill-hammer/

# ANNEX



Notes:
1. * - informational dimension

| Cutting based on EN - ISO 9013:2002 class 1 | | | Part Number | | | | |
|---|---|---|---|---|---|---|---|
| | Made by | Signature | Date | Title | | Mass, kg | Scale |
| | | | | Hammer | | 0,63 | 1:1 |
| | | | | | Sheet 1 | Of 1 | |
| Designer | | | | Material | | | |
| Revised by | | | | | | | |
| Approved by | | | | | | | |

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