Cut Cost Calculation

Johan Berglund

MASTER OF SCIENCE PROGRAMME
Industrial Economics

Luleå University of Technology
Department of Applied Physics and Mechanical Engineering
Division of Manufacturing Systems Engineering
Abstract

SSAB Oxelösund is a member of the SSAB Svenskt Stål AB Group and is the biggest Nordic manufacturer of heavy steel plate. SSAB Oxelösund’s main products are the hardened wear plate HARDOX and the high strength structural plate WELDOX. The most common processes that are used to cut the steel are the thermal processes oxyfuel, laser and plasma as well as the non-thermal process abrasive water jet. Cutting HARDOX using one of the thermal processes can result in edge cracking. In addition, if a thermal process is used to cut small parts, the hardness of the steel is affected. Therefore, SSAB wishes to have a computer based calculation application that would provide guidance regarding how to best cut SSAB’s different steels, in particular HARDOX.

It was found that the main features that users wanted in this application were to be able calculate the cost of a cutting job, to be able to compare the costs of oxyfuel cutting with and without preheating and to see when abrasive water jet cutting is a viable option.

It was also found that it is possible to calculate the costs involved in the different cutting processes quite accurately. However, to calculate the costs involved in preheating before cutting with oxyfuel it is recommended to develop a more complex calculation model.

The recommendation is for SSAB to continue developing an application to help its customers calculate their cutting costs. It is also to use the application to influence customers to use cutting methods and cutting speeds that does not produce edge cracking. This would benefit both SSAB and its customers as it makes SSAB seem knowledgeable about the problems that the customers face and also help the customers to be more productive.
# Table of contents

1 Introduction 4  
1.1 Background and aim 4  
1.2 Methods used 5  

2 Cutting processes 6  
2.1 Abrasive water jet cutting 6  
2.2 Laser cutting 8  
2.3 Oxyfuel cutting 10  
2.4 Plasma arc cutting 12  

3 Cut quality 16  
3.1 ISO 9013 16  
3.2 Other quality measurements 18  

4 Cut edge cracking 20  
4.1 Edge cracking 20  
4.2 Methods to avoid edge cracking 21  

5 Preheating experiments 24  
5.1 Results 26  
5.2 Analysis 26  

6 Interviews 27  

7 Calculation models 30  
7.1 Results 30  
7.1.1 Abrasive water jet 31  
7.1.2 Laser 32  
7.1.3 Oxyfuel 33  
7.1.4 Plasma 35  
7.2 Analysis 36
7.2.1  Oxyfuel with and without preheating  
7.2.2  Cutting of HARDOX 600  

8  Application structure  
8.1  Cost calculation  
8.2  Recommended cutting speeds  
8.3  Cutting methods  
8.4  Troubleshooting  
8.5  Configuration  

9  Conclusions and recommendations  

10  References  
10.1  Books and reports  
10.2  Personal contacts and interviews
1 Introduction

1.1 Background and aim

SSAB Oxelösund’s main products are the hardened wear plate HARDOX and the high strength structural plate WELDOX. For SSAB’s customers, the first step is usually some kind of cutting process before the steel can be integrated in the customers’ own products. The most common cutting processes that are used are the thermal processes oxyfuel, laser and plasma as well as the non-thermal process abrasive water jet.

However, cutting HARDOX using one of the thermal processes can result in edge cracking. Additionally, if a thermal process is used to cut small parts, the hardness of the steel can be severely affected.

Therefore, SSAB wishes to have a computer based calculation application that would provide guidance regarding how to best cut SSAB’s different steels, in particular HARDOX. The aim of this thesis is to present a basic structure for such an application. The application should help SSAB’s customers to reduce the risk of cut edge cracking by giving recommendations regarding choice of cutting process and cutting speed. The recommendations should be supported by economic calculations and show that it is cheaper to cut in a way that does not result in edge cracking.

The target group for this application is foremost SSAB Oxelösund’s customers that buy HARDOX, more specifically the persons in those organisations that make the decisions concerning cutting processes, cutting speeds et cetera. Another target group is SSAB Oxelösund’s own application engineers that would use the application to give advice to customers and to help solve problems.
By developing and distributing an application like the one described above, SSAB wants to show its customers that SSAB is knowledgeable about the problems that the customers face and that they are willing to provide help and advice regarding how to deal with the problems. In addition, it is a way to give further weight to recommendations such as preheating before oxyfuel-cutting. If it can be shown that it is cheaper to do a certain operation in a certain way it is more likely that the customer will do it in that way.

1.2 Methods used

The methods used to create this thesis are:

- A study of litterateur was carried out to get an understanding of how the different cutting processes and cut edge cracking work and how to avoid edge cracking as well as how cutting costs are calculated. Different reports and specialist books were studied.

- Some practical experiments were conducted to make it possible to approximate the time it takes to preheat a steel plate.

- A series of interviews were carried out to identify SSAB’s customers’ and applications engineers’ needs in an application like the one described above as well as to get a deeper understanding of how cutting costs are calculated in different organisations.
2 Cutting processes

2.1 Abrasive water jet cutting

Abrasive water jet (AWJ) cutting is a cold, non-thermal, cutting process. The system uses high-pressure water, which is passed through a fine bore nozzle to form a coherent, high velocity jet.

A water jet itself has sufficient power to cut most non-metallic materials such as rubber, leather and plastic. However, abrasive particles, such as flint or garnet, must be entrained in the jet for cutting metals and ceramics. The cutting performance of the equipment is limited by a number of factors including traverse rate, abrasive type and feed rate, standoff distance, and pump capacity.

AWJ cutting of the work piece results from a combination of erosion and micro machining effects, depending on the specific properties of the material. Micro machining refers to the removal of small amounts of the work piece material by abrasive particles. The cutting action results in a striation effect on the surface of the cut edge, and the drag angle of the sensations depends on the relationship between traverse speed and cutting power. As the cutting speed increases for a given cutting power, the angle of the sensations will increase until through thickness cutting is no longer achieved. The cutting power depends on water pressure and abrasive feed rate.

The most important advantage of the process is its ability to cut materials without heat, thus avoiding the formation of heat affected zones in metals, which can, in some instances, result in micro cracking in higher strength metallic alloys. This also
applies to plastics and composite materials where thermal cutting often degrades or chars the edges of the material being cut. Sandwich materials are being used more extensively in industry and, with large differences in melting points, a non-thermal cutting process is the only alternative. Another important advantage of this process is that high quality cut edges are produced which require no subsequent edge finishing operations.

There are three distinct types of cutting equipment available, characterised mainly by the water pressures used and the abrasive entrainment system employed:

1. Standard entrainment
2. Standard entrainment with higher pressures
3. Direct entrainment

Standard entrainment, mixing water and abrasive in a chamber immediately adjacent to the cutting nozzle, with operating pressures in the region of 700 bar and a typical nozzle diameter of 3 mm.

Standard entrainment with higher pressures, similar to standard entrainment but pressures in the range 2,000 to 4,000 bar and a typical nozzle diameter of 1 mm. The standard entrainment system with high operating pressure and small bore nozzle produces an extremely powerful jet that is capable of cutting 100 mm thick steel with a kerf width of approximately 2 mm. The process is used for precision cutting applications.

Direct entrainment, an abrasive mixing system with pressurisation of the water and abrasive particles in a small pressure vessel, with operating pressures of up to 700 bar and a typical nozzle diameter of 3 mm. Direct entrainment produces higher energy efficiency which can achieve a five-fold increase in the cutting speed compared to a standard entrainment system at the same operating pressure. The kerf width is somewhat greater at typically 3 mm because of the larger bore nozzles.

The standard entrainment systems are generally used in manufacturing environments for precision cutting of almost any material including those that are difficult to cut, in example composites and some ceramics. AWJ cutting equipment is often found in workshops, possibly alongside laser and plasma cutting systems, where a wide range of metallic and non-metallic sheet and slab products can be handled.
The direct entrainment system is usually used in contracting industries for tasks such as demolition of steel and concrete structures. The systems have also been employed for difficult cutting operations, often in hazardous environments such as in the repair and upgrade of plant in chemical, oil and gas, and offshore industries and in the cutting of munitions. This is due to the very low fire risk associated with the process compared to thermal cutting processes.\textsuperscript{1,2}

\textbf{Figure 1: Standard entrainment abrasive water jet cutting head}

\subsection*{2.2 Laser cutting}

There are two commonly used types of industrial cutting laser, CO\textsubscript{2} and Nd:YAG. These differ in that the wavelength of infrared light produced is 10.6 \textmu m for CO\textsubscript{2} lasers and 1.06 \textmu m for Nd:YAG lasers. Both these types of lasers cut by focusing a beam of monochromatic light to a very small spot size by lenses and mirrors giving power densities up to \(10^5\) W/mm\textsuperscript{2}. This power density is sufficient to locally melt or even vaporise most materials. Once a through thickness zone of molten or vaporised material is generated, a jet of assist gas, delivered co-axially through the cutting nozzle, ejects this material from the kerf.
The difference in wavelength between the two types of lasers is significant as the shorter wavelength of the Nd:YAG laser enables the light to be transmitted to the work piece by fibre optics allowing three dimensional cutting or trimming of parts. Light from CO\textsubscript{2} lasers on the other hand is transmitted to the work piece by mirrors or transmissive optics. Because of this, CO\textsubscript{2} lasers are mostly used for two dimensional flat bed cutting.

The characteristics of the laser cutting process relate to the fact that the beam can be focused to a spot of less than 0.5mm diameter to achieve these very high power densities. The resulting cut edge is very square and the process is capable of cutting at very high speeds. The combination of an intensely concentrated heat source moving at high speeds also results in very little heat being transmitted to the surrounding material and, therefore, very little thermal distortion of parts.

Nd:YAG cutting lasers usually operate in pulsed mode, although some have been developed to operate in continuous wave mode. When using the latter, cutting takes place in a similar manner to CO\textsubscript{2} laser cutting where the laser cutting head is moved relative to the work piece at a speed that allows stable cutting to take place. In contrast, pulsed Nd:YAG laser cutting is an extension of drilling where overlapping holes are created by moving the focused laser beam relative to the work piece. The power of a pulsed Nd:YAG laser is usually quoted in terms of average power but, depending on type, pulse peak power may be ten to twenty times greater.

The types of assist gases used to eject the material from the kerf can be classified as either reactive or inert. The most commonly used reactive assist gases are oxygen or air. Oxygen is used primarily for cutting low alloy steels and readily reacts with iron at high temperatures producing additional heat energy which enables thicker parts to be cut or greater speeds to be achieved. This gas is delivered at relatively low pressures and flow rates and the process is referred to as low-pressure oxygen cutting.

Inert assist gases commonly used are either nitrogen or argon. These provide no thermal assistance to the cutting process and are used simply to blow the molten material out of the kerf. They are used at pressures of around 10 bar and the process is referred to as high-pressure inert gas cutting. Inert gases can be used for alloys that readily oxidise in the presence of oxygen such as stainless steel, aluminium or titanium to give a very bright and clean-cut edge. Inert gases are recommended for cutting low alloy steels where the edges are to be subsequently laser welded. This is
due to the reduced formation of an oxidised layer on the face of the cut edge and will reduce porosity in the resulting weld.

Metals, ceramics, polymers and natural materials such as wood and rubber can all be cut using lasers. For steels the dominant process utilises an oxygen assist gas, which provides exothermic energy to the cutting process. As a result, thick sections, up to 20 mm, can be cut commercially and the cut quality and speed are generally considered high when compared with other thermal cutting processes. Laser cutting is also generally regarded as a low-distortion process, compared with other thermal cutting options.³,⁴

![Laser cutting head](image)

**Figure 2: Laser cutting head**

### 2.3 Oxyfuel cutting

A mixture of oxygen and fuel gas is used to preheat the metal to its ignition temperature but below its melting point. The ignitions temperature for steel is 700 to 900 °C, bright red heat. A jet of pure oxygen is then directed into the preheated area setting off an exothermic chemical reaction between the oxygen and the metal to form iron oxide, slag. The oxygen jet blows away the slag enabling the jet to pierce through the material and continue the cut through the material.

In theory, the oxyfuel process may cut any alloy provided that the metal burns when heated above its flash point temperature in the presence of oxygen and the flash point temperature lies below the melting point. In practice the process is effectively limited to low alloy steels with less than 5% Cr, 5% Mo, 5% Mn, 9% Ni and 10% W.
There are four basic requirements for oxyfuel cutting:

1. The ignition temperature of the material must be lower than its melting point. Otherwise the material would melt and flow away before cutting could take place.
2. The oxide melting point must be lower than that of the surrounding material so that it can be mechanically blown away by the oxygen jet.
3. The oxidation reaction between the oxygen jet and the metal must be sufficient to maintain the ignition temperature.
4. A minimum of gaseous reaction products should be produced so the cutting oxygen is not too polluted.

The cutting nozzle, from which the jet of oxygen emerges, has a large influence upon cutting speed and cut quality. There are two common types of cutting nozzles: standard and high-speed. The standard, parallel orifice nozzle is used for both manual and machine cutting. The high-speed nozzles are capable of being used with higher oxygen pressures that enable the cutting speed to be increased significantly, especially in machine cutting. The essential difference between the standard and high-speed nozzles is that the orifice is smaller and diverging for the high-speed nozzle.

The cutting oxygen pressure depends on the plate thickness, the cutting nozzle and nozzle system. The pressure usually lies in the range of 3 to 9 bar. If the cutting oxygen pressure is too high the width of the cut will increase downwards in width in the kerf and notching in the cut edge can occur. If the oxygen pressure is too low the oxygen flow rate becomes to slow causing poor cut edge quality and difficulties to cut through the steel.

The cutting speed and cut edge quality are primarily determined by the purity of the oxygen stream. Thus, nozzle design plays a significant role in protecting the oxygen stream from the surrounding air. The purity of oxygen should be at least 99.5%. A decrease in purity of 1% will typically reduce the cutting speed by 25% and increase the gas consumption by 25%.

The fuel used in the burner is usually one of acetylene, propane, MAPP (methylacetylene-propadiene), propylene or methane. The relative performance of the fuel gases in terms of pierce time, cutting speed and cut edge quality, is determined by the flame temperature and heat distribution within the inner and outer flame cones.
Fuel gas combustion occurs in two distinct zones. In the inner cone, or primary flame, the fuel gas combines with oxygen to form carbon monoxide and hydrogen. Combustion also continues in the secondary, or outer, zone of the flame with oxygen being supplied from the air.

The oxyfuel process is the most widely applied industrial thermal cutting process principally because it can cut thicknesses from 0.5 to 2,500 mm, the equipment is low cost and can be used manually or mechanised. There are several fuel gas and nozzle design options that can significantly enhance performance in terms of cut quality and cutting speed.

Because the cost of the cutting torch is low compared with the price of the manipulation equipment, it is common to fit several torches to each cutting table.

![Figure 3: Cutting nozzle for oxyfuel cutting](image)

2.4 Plasma arc cutting

Plasma arc cutting is a melting process in which a jet of ionized gas at temperatures above 30,000 °C is used to melt and eject material from the cut. During the process an electric arc is struck between an electrode (cathode), and the work piece (anode). The electrode is recessed in a water or air cooled gas nozzle which constricts the arc causing the narrow, high temperature, high velocity plasma jet to form. When this jet hits the work piece and the gas reverts to its normal state, heat is emitted. This heat melts the metal and the gas flow ejects it from the cut. Plasma arc cutting can be used to cut a wide range of electrically conductive alloys including plain carbon and stainless steels, aluminium, nickel alloys and titanium.
The method was originally developed to cut those materials that could not be cut by the oxyfuel process. Because of this, plasma arc cutting has always been seen as an alternative to the oxyfuel process. However, the important difference between the two processes is that while the oxyfuel process oxidises the metal and the heat from the exothermic reaction melts the metal, the plasma process operates by using the heat from the arc to melt the metal. The ability to melt the metal without oxidation is essential when cutting metals which form oxides with high melting points, such as stainless steel. Therefore, the plasma process was first introduced for cutting stainless steel and aluminium alloys.

The basic plasma torch consists of a central tungsten electrode for forming the arc but unlike in the conventional TIG welding process, a fine bore copper nozzle constricts the arc. This has the effect of increasing the temperature and velocity of the plasma emanating from the nozzle.

There are a number of designs of the plasma cutting head. The exact design is dependent on the manufacturer and it is difficult to draw general conclusions on the performance of different heads. However, the main design principles of the plasma cutting head are to constrict the plasma, to increase the temperature and velocity of the plasma emanating from the nozzle and to reduce operating costs, through use of cheap plasma or shielding gases, such as air.

Dual gas: The process operates basically in the same manner as the conventional system but a secondary gas shield is introduced around the nozzle. The cutting gas is normally argon, argon/H₂ or nitrogen and the secondary gas is selected according to the metal being cut. For example, when cutting mild steel, air or oxygen can be used to increase the cutting speed.
Water injection: Water can be injected into the plasma arc to induce a greater degree of constriction. The temperature of the plasma is considerably increased, which facilitates higher cutting speeds and, because of the greater constriction of the arc, the cut quality is much improved. The presence of a film of water around the plasma protects the nozzle bore, reducing nozzle erosion.

Water shroud: The plasma arc can also be operated either with a water shroud or even with the work piece submerged in water. The water will act as a barrier in reducing fume and noise levels. In a specific example, noise levels can be as high as 115 dB, this can be reduced to about 96 dB with a water shroud and reduced to 52 to 85 dB when cutting underwater. Another benefit of cutting underwater is that the risk of softening of the cut component will be kept to a minimum.

Air plasma: The inert or non-reactive plasma forming gas, argon or nitrogen, can be replaced with air but this requires a special electrode of hafnium or zirconium mounted in a copper holder. The use of compressed air instead of the more expensive cylinder gas makes this variant of the plasma arc process highly competitive with the oxyfuel process. A variant of the air plasma process is the mono-gas torch in which air is used for both the plasma and the cooling gas.

High tolerance plasma: In an attempt to improve cut quality and to compete with the superior cut quality of laser systems, a number of plasma systems are available commercially which operate with a highly constricted plasma arc. Systems under the generic name high-tolerance plasma arc cutting, HTPAC, are manufactured by Hypertherm, Koike Aronson and Komatsu-Cybernation. The common features of the torches are that the oxygen plasma jet is forced to swirl as it enters the plasma orifice and a secondary flow of gas is injected down stream of the plasma nozzle. Some torches have a separate magnetic field surrounding the arc that stabilises it by maintaining the rotation induced by the swirling gas.

There are many combinations of gases that can be used for plasma arc cutting in the plasma itself and in the shield. It should be noted that improved performances may be gained in specific instances with the correct selection of plasma and shielding gas mixtures.

Plasma gases used when cutting C-Mn steels consist of air, oxygen or nitrogen. Inert gases are preferred for high quality cuts in reactive alloys.
When using air or nitrogen as plasma gas the cut edge surface will be supersaturated in terms of nitrogen causing pore formations upon welding.

With plasma arc cutting angle deviation can be a problem. The effect will be more pronounced the thicker the plate being cut is. The amount of deviation depends on the plasma gas used. Using air or nitrogen creates the largest deviation.

![Diagram](image)

*Figure 5: Angel deviation when plasma arc cutting*

The main usage of plasma arc cutting is cutting mild and stainless steels as well as aluminium alloys, though the process can cut any metal. Because the cost of the plasma torch is low compared with the price of the manipulation equipment, it is common to fit several torches to each cutting table.\(^5\,^6\)
3 Cut quality

The dimensional accuracy of a cut is important as it helps to ensure correct part tolerances and fit-up, thus eliminating rework or secondary processing operations further down the production line. Precision is not solely dependent upon the cutting process but is also dependent upon the machine and its control capability, the thickness of material being cut and any thermal distortion effects during the process.

3.1 ISO 9013

The international industrial standard ISO 9013 deals with the subject of thermal cutting in terms of definitions, methods and quality of classification of thermally cut surfaces.

Kerf is defined as the width of the cut at its widest point in millimetres and gives an indication of the minimum internal radius or feature that can be cut. The kerf width also affects the cutting path necessary to achieve the required dimensional accuracy.

Cut edge roughness is used to define the cosmetic appearance of a cut and can give an indication of whether subsequent machining operations are necessary. Cut edge roughness is determined by an Rₐ value in microns, also known as the ISO 10 point height parameter, and is measured using a Taly-Surf type machine. This device has a mechanical stylus that moves along the cut edge. The mechanical movement is converted into an electrical signal that is amplified, recorded and analysed. In accordance with ISO 9013 measurements should be made 2/3 of the material thickness below the top surface. ISO 4827-1 describes the parameters used to define surface roughness.
Edge squareness is of interest because it gives an indication of the fit-up between two components and whether any post cutting machining operations will be necessary. It is defined in terms of the perpendicularity and angularity tolerance, U, which is defined as the distance between two parallel straight lines that limit the upper and lower boundaries of the cut face profile at the theoretically correct angle, 90 degrees for square cut edges. The standard establishes a zone of significance for the measurement of U reduced at the top and bottom edge by a distance, Δa, related to material thickness, a, as specified in the standard.

![Diagram](https://via.placeholder.com/150)

*Figure 6: U, the perpendicularity and angularity tolerance*

According to the standard ISO 9013, the quality of the cut is classified into three zones. 10
3.2 Other quality measurements

There are other ways of evaluating cut quality besides ISO 9013, where other relevant factors are taken into consideration.

Drag, \( n \), is the projected distance between the two edges of a drag line in the direction of cutting.
Figure 8: Drag lines

The top edge rounding indicates the shape of the top edge of the cut. It can either be sharp or rounded, with or without overhang.

HAZ width is defined as the width of a detectable micro structural change measured perpendicular to the cut edge face. This is only applicable to alloys that are hardenable or heat treatable. The width of the HAZ is of interest because, due to the region's possible greater brittleness or susceptibility to crack initiation, this material may have to be removed before final assembly of a product. It is also a measure of the amount of heat transmitted to the parent material, which, in turn, can be related to thermal distortion. For some thermal cutting processes, the width can vary through the thickness.

Dross describes the resolidified material that sticks on to the bottom edge of a cut, when a thermal cutting process is used. Excessive dross can lead to problems with component fit-up and additional costs are created in the removal. The level of dross is measured subjectively, and the terms most commonly used are none, light, medium and heavy. However, with the correct processing parameters, it is possible to eliminate dross, or reduce it to a minimum.  

3, 4
4 Cut edge cracking

4.1 Edge cracking

When using a thermal cutting process to cut high strength steel there is always the risk of cracking. This applies to all thermal cutting processes but is extra evident in oxyfuel cutting due to the high amount of heat that is transferred. The cut edge cracking susceptibility increases with increasing plate hardness and thickness.

Just like with welding the hydrogen content in the steel plays a determining role for the cutting crack susceptibility. The thicker the plate the more alloys it contains and thus becomes more sensitive to cracking.

The residual stresses in the plate increase with plate thickness and hardness. High residual stress is not beneficial since the stress tends to open up small cracks giving them an increased force to propagate.

Micro segregations are always present to some extent. The effect of segregations on the cutting crack susceptibility increases with plate hardness, plate thickness and residual stress level. By summarising these arguments it can be concluded that the harder the steel is the more susceptible it is to cut edge cracking.

The cracks start as embryos close behind the cut edge near the centre of the cross section. The length of de cracks can vary from less then 1 mm to about 40 mm. The depth of the crack is no more than a couple of millimetres and located parallel to the plate surface. These cracks are not visible and could only be detected through ultrasonic inspection.
If the cracks start to propagate they become clearly visible at the cut edge. When cracks reach this stage it is advisable to machine the cut edges or to perform a new cut with increased precision in respect to the cutting recommendations. If the component is to be welded, joint preparation by machining is recommended.

The centre line visible edge cracks can propagate further. They can either increase in length and depth or change orientation, which is more likely. From running parallel to the plate the crack twists and change direction running vertical to the plate thickness. When the crack reaches the plate surface, and sometimes even through the plate cross-section, it can propagate up to 0.5 - 1 m in length and split entire plates.

Depending on the circumstances under which the cutting took place the pace of the crack event can vary in time. If cutting in hard steels has been performed at speeds used for conventional steels of the same thickness the cracks can appear as early as one to six hours after cutting. However, since the susceptibility to develop these cracks depend upon factors as residual stresses, steel hydrogen level, presents of micro segregation and plate thickness it is as likely that these cracks appear much later. Observations made have shown that cracking of plates can appear up to 6 month after being cut.

To keep a steady production flow it is important for the manufacturer that the components get assembled into a final product, often by welding. If the component is welded, new residual stress fields will be built up around the cut edge thus helping the cracks to start propagate. Weld cracking that looks like weld hydrogen cracking can in many cases actually originate from cut edge cracking, developed prior to welding.\textsuperscript{7,8}

4.2 Methods to avoid edge cracking

The simplest way to avoid edge cracking is to use an abrasive water jet instead of an oxyfuel process to cut the plate. However, when this is not possible there are different ways to reduce the risk of cut edge cracking.

Preheating is the most reliable method to avoid problems with cut edge cracking and it maintains the work piece at elevated temperature throughout the entire cutting process.

Preheating can be performed either by placing the entire plate in a furnace or by using electrical heating mats. If furnace or heating mats are not available preheating can be performed using a heating torch.
The heating mats the width of about 100 mm should be placed along the plate where the cut is to be made. The preheat temperature should be measured on the opposite side of the plate to where the heating mats are placed.

A method, that is very simple to implement, to reduce or eliminate the risk of edge cracking is to make the cut at a reduced cutting speed. If the cutting speed is reduced to around 30% of the normal cutting speed enough heat is transferred to the cut edge to make it cool down at a rate slow enough not to develop cracks. However, when thicker plates are cut at reduced cutting speeds the resulting cut edge can be very rough.

![Figure 9: Parts of the same 100 mm plate, on the left cut at a reduced speed, on the right preheated then cut at normal speed](image)

Keeping the plate at elevated temperature a certain time after cutting also contributes to minimise the cut edge crack susceptibility of the steel. The temperature at which the post heating should be performed is the same as the recommended preheating temperature. Time of tempering depends on the plate thickness.

In many cases it is not necessary to use post heating. Instead an extension of the cooling time after cutting can be enough to prevent formation of edge cracking. Just insulating the area around the cut with mineral wool or similar can do this.

Directly after cutting, the components and remains of the plate must slowly be cooled down to an even temperature, most often to room temperature. The steel should not be exposed to heavy temperature changes before it has cooled down.
For example, when cutting components in HARDOX 500 or 600, of plate thicknesses more than 30 mm, it is recommended that they are stored indoors at least 24 hours after the cutting has been preformed.

It is recommended that visual inspection of the cut edges is preformed. The longer the time between cutting and inspection the better it is.\textsuperscript{8,9}
5 Preheating experiments

The objective of the preheating experiments was to get an idea of how much time it takes to preheat a steel plate to a certain temperature to be able to approximate the costs of gases, machine time and so on. The aim was not to develop a general calculation model for the cost of preheating but simply to see how the material thickness affected the heating time with an already installed preheating equipment. All experiments were carried out by the same persons and with the same equipment.

Steel plates the size of 1 x 2 metres with different thicknesses had temperature sensors attached to them and were then heated while the temperatures were logged. Four sensors were used, two were placed on the top surface of the plate, one in the centre and one close to the edge, and the other two were placed on the bottom surface, directly below the first two sensors.

![Figure 10: Placement of the temperature sensors](image)

The heating equipment used is from Linde AG and uses acetylene and compressed air to heat the steel. The combination of acetylene and compressed air is chosen for
this type of application because the flames do not get very hot. If the temperature in the plate exceeds 250 °C the hardness of the plate will be affected which is undesirable.

![Flame heating of steel plate](image)

*Figure 11: Flame heating of steel plate*

Since the steel plate conducts heat very well it is possible to approximate the temperature in the middle of the plate to be fairly close to the temperature at sensor 2. A heating process is non linear, however, in this very limited temperature interval the process can be approximated to be linear, as can be seen in the log outputs. The heated plates had thicknesses of 30, 60, 80 and 100 mm.
5.1 Results

The results of these experiments are in the form of log outputs and calculations. In this section, a summary of the results is presented. For more detailed information, calculations and log outputs see Appendix 1.

![Figure 12: Log output from heating experiment with a 30 mm HARDOX600 plate](image)

The results show that it is possible to estimate the time it takes to heat a plate to a certain preheat temperature under these specific circumstances fairly well with the following model:

\[
x = \frac{t(y - m - 5)}{180}
\]

where \(x\) = time (min), \(t\) = plate thickness (mm), \(y\) = preheat temperature (°C) and \(m\) = start temperature (°C). For example, it should take approximately 20 minutes to heat a 30 mm thick plate from 20 to 150 degrees Celsius.

5.2 Analysis

The accuracy of this calculation model is about ±5 minutes, which is more than precise enough to approximate the costs of gases, machine time etc.

The results from these experiments are only valid for plates the size of 1 x 2 meters and with this kind of heating equipment.
6 Interviews

The interviews and personal discussions raised several important questions and brought a lot of different opinions to light. This section is an account and analysis of the most relevant issues that were discussed. The interviews also gave insight regarding how different organisations calculate their costs associated to steel cutting. How these costs are calculated is described in more detail in section 7.

In an application like the one described in section 1.1, when the user chooses a material to cut, should it be possible to input an arbitrary chemical analysis or should the user be limited to a choice of SSAB steels?

The advantage of this would be that the application would be more useful from the customer’s point of view. The disadvantages are that it would probably be very hard to implement in an application that is supposed to take into consideration the steel manufacturer’s recommendations regarding cutting speeds and so on. Moreover, some of SSAB’s competitive edge of having an application like this closely connected to its own products is lost if it is possible to use in connection with products from other manufacturers.

If the main purpose of the application is to add value to SSAB’s products and not to be a very useful application on its own it doesn’t seem to make sense to let the user enter an arbitrary chemical analysis into the application.

Different limitations can be associated with different cutting methods, for example, it is not so common to use very large cutting tables in combination with abrasive water jet cutting as it is with plasma arc cutting. Different sizes of the cutting tables can affect the total productivity due to the possibilities regarding changing work pieces
and so on. Is this something that would be interesting to take into consideration in the application?

Obviously, some kind of limitation has to be decided upon concerning what type of costs the application should take into consideration. For example, there are an unlimited number of possible combinations of handling equipment that could be present in a certain workshop. Different handling equipment mean different levels of efficiency and different levels of utilisation of the cutting equipment. To avoid all of these potential problems it is best to choose to only include utilisation of the cutting machines and leave the rest to the user to take into consideration.

*When ordering steel plates from SSAB, there is the choice of three different primer thicknesses: none, thin and thick. Should this be one of the parameters in the application?*

The primer only affects the cutting when using laser cutting and is in fact a very important factor. The thicker the primer, the harder it will be to cut with laser. However, a thinner but not evenly thick layer of primer is worse. This is because when the laser hits a spot of thicker primer there is a good chance that the beam will be interrupted and the cutting will have to be restarted.

It is possible, and probably reasonable, to implement a parameter to describe the thickness of the primer in the application, either just as the choice of primer or no primer or a more complex choice of different primers.

One of the interviewed persons mostly saw two uses for an application of this kind. First of all, it could be used as a support when evaluating different investments. For example, an applications engineer together with a customer could do this so that the customer can be advised regarding what type of equipment to buy. The second use was optimisation of already existing cutting equipment. An example of this could be a customer that uses the application to check the recommended cutting speed for a certain cutting method given the material and thickness.

A common way to calculate cutting costs is to calculate a theoretical total cutting time and then simply multiply that with a fixed hourly cost for the machine that is going to be used.
The main features that future users wanted in an application like the one discussed were:

- To calculate the cost of a cutting job
- To be able to compare the costs of oxyfuel cutting with and without preheating
- To see when abrasive water jet cutting is a viable option
7 Calculation models

The calculation models have been derived from general calculation models used in manufacturing economics and through discussions with persons with experience in calculating cutting costs.

7.1 Results

To denote units of money the Euro (€) is used, however, any currency can be used.

There are several variables that the different calculation models have in common. The following variables are the basic variables required to do a cost calculation:

\[
\begin{align*}
\text{Np} & = \text{number of parts}. \text{ The number of parts in a batch.} \\
\text{Nstp} & = \text{number of cut starts per part}. \text{ For example, when cutting a part with a hole in it, the cutting process has to be started twice, one time for the peripheral profile and one time for the hole.} \\
\text{Lcutp} & = \text{length of cut per part} \text{. (m)} \\
\text{Nsh} & = \text{number of shifts}. \\
\text{Plab} & = \text{cost of labour} \text{. (€/h)} \\
\text{Pcap} & = \text{the invested capital} \text{. (€)} \\
\text{U} & = \text{utilisation} \text{. (%)} \\
\text{Nop} & = \text{number of operating hours per year and shift} \text{. (€)} \\
\text{Tmach} & = \text{machine life expectancy, depreciation time} \text{. (years)} \\
\text{Int} & = \text{annual interest} \text{. (%/year)} \\
\text{Ins} & = \text{insurance (} \% \text{ of Pcap/year)} \\
\text{Sreq} & = \text{required space} \text{. (m}^2\text{)} \\
\text{Prent} & = \text{rent} \text{. (€/m}^2\text{ and month)} \\
\text{Maint} & = \text{maintenance} \text{. (} \% \text{ of Pcap and year)}
\end{align*}
\]
T\text{prep} = \text{time for preparation. NC-programming etc. (h)}

Pel = \text{price of electricity. (€/kWh)}

Elp = \text{electric power consumption. (kW)}

Although information about material and material thickness also is needed, those variables are not used directly in the calculation, but are used to determine the cutting speed and the consumption of gases.

7.1.1 Abrasive water jet

When abrasive water jet is the chosen cutting method for a cost calculation, a few variables specific to that cutting method has to be taken into account:

Npt = \text{number of parallel torches.}

Pab = \text{price of abrasive. (€/kg)}

Ttip = \text{tip life. (h/tip)}

Ptip = \text{tip price. (€/tip)}

Conab = \text{consumption of abrasive. (kg/h)}

Cutsp = \text{cutting speed. (m/min)}

Tst = \text{time of cut start, penetration and movement. (s)}

The cost calculation for an abrasive water jet cutting job is given by:

\text{Cost of abrasive: Conab} * \text{Pab} = \text{Cabh (€/h)}

\text{Cost of electricity: Elp} * \text{Pel} = \text{Celh (€/h)}

\text{Number of machine hours per year: Nop} * \text{Nsh} * \text{U} * 0.01 = \text{Nopy (h)}

\text{Cost of interest: Pcap} * 0.5 * \text{Int} * 0.01 = \text{Cint (€/year)}

\text{Cost of depreciation: Pcap} / \text{Tmash} = \text{Cdep (€/year)}

\text{Cost of insurance: Pcap} * \text{Ins} * 0.01 = \text{Cins (€/year)}

\text{Cost of space: Sreq} * \text{Prent} * 12 = \text{Cs (€/year)}

\text{Cost of maintenance: Pcap} * \text{Maint} * 0.01 = \text{Cmaint (€/year)}

\text{Rate per machine hour:} (\text{Cint} + \text{Cdep} + \text{Cins} + \text{Cs} + \text{Cmaint}) / \text{Nopy} = \text{Rmh (€/h)}

\text{Number of tips: 1} / \text{Ttip} = \text{Contip (tip/h)}

\text{Cost of tips: Contip} * \text{Ptip} * \text{Npt} = \text{Ctiph (€/h)}

\text{Total cut length: Lcutp} * \text{Np} = \text{Lcuttot (m)}
Total time of cut starts: \((Nstp \times Tst \times Np) / 3600 = Tsttot\) (h)
Total time of cutting: \((Lcuttot / (Cutsp \times 60) + Tsttot) / Npt = Tcuttot\) (h)

Total cost of labour: \(Plab \times (Tprep + Tcuttot) = Clabtot\) (€)
Total cost of electricity: \(Celtot = Celh \times Tcuttot\) (€)
Total cost of abrasive: \(Cabtot = Cabh \times Tcuttot\) (€)
Total cost of machine hours: \(Cmhtot = Rmh \times Tcuttot\) (€)
Total cost of tips: \(Ctiptot = Ctiph \times Tcuttot\) (€)

Total cutting cost: \(Clabtot + Celtot + Cabtot + Cmhtot + Ctiptot = Ctot\) (€)

7.1.2 Laser

In addition to the variables from section 7.1, the following variables specific to laser cutting has to be taken into account:

\[
\begin{align*}
\text{Pcgas} &= \text{price of cutting gas. (€/m}^3) \\
\text{Plgas} &= \text{price of laser gas. (€/m}^3) \\
\text{Ttip} &= \text{tip life. (h/tip)} \\
\text{Ptip} &= \text{tip price. (€/tip)} \\
\text{Tlens} &= \text{lens life. (h/lens)} \\
\text{Plens} &= \text{lens price. (€/lens)} \\
\text{Cutsp} &= \text{cutting speed. (m/min)} \\
\text{Tst} &= \text{time of cut start, penetration and movement. (s)} \\
\text{Concgas} &= \text{consumption of cutting gas. (l/h)} \\
\text{Conlgas} &= \text{consumption of laser gas. (l/h)}
\end{align*}
\]

The total cut cost for a laser cutting job is given by:

Cost of gases: \((Concgas \times Pcgas + Conlgas \times Plgas) / 1000 = Cgash\) (€/h)

Cost of electricity: \(E_{lp} \times Pel = Celh\) (€/h)

Number of machine hours per year: \(Nop \times Nsh \times U \times 0.01 = Nopy\) (h)
Cost of interest: \(Pcap \times 0.5 \times Int \times 0.01 = Cint\) (€/year)
Cost of depreciation: \(Pcap / Tmach = Cdep\) (€/year)
Cost of insurance: \(Pcap \times Ins \times 0.01 = Cins\) (€/year)
Cost of space: \(Sreq \times Prent \times 12 = Cs\) (€/year)
Cost of maintenance: \(Pcap \times Maint \times 0.01 = Cmaint\) (€/year)
Rate per machine hour: \((Cint + Cdep + Cins + Cs + Cmaint) / Nopy = Rmh\) (€/h)
Number of tips: 1 / $T_{tip} = C_{tip}$ (tip/h)
Cost of tips: $C_{tip} \times P_{tip} = C_{tiph}$ (€/h)

Number of lenses: 1 / $T_{lens} = C_{lens}$ (tip/h)
Cost of lenses: $C_{lens} \times P_{lens} = C_{lensh}$ (€/h)

Total cut length: $L_{cutp} \times N_{p} = L_{cuttot}$ (m)
Total time of cut starts: $(N_{stp} \times T_{st} \times N_{p}) / 3600 = T_{sttot}$ (h)
Total time of cutting: $L_{cuttot} / (C_{uts} \times 60) + T_{sttot} = T_{cuttot}$ (h)

Total cost of labour: $P_{lab} \times (T_{prep} + T_{cuttot}) = C_{labtot}$ (€)
Total cost of electricity: $C_{elt} \times T_{cuttot} = C_{elot}$ (€)
Total cost of gases: $C_{gash} \times T_{cuttot} = C_{gastot}$ (€)
Total cost of machine hours: $R_{mh} \times T_{cuttot} = C_{mhtot}$ (€)
Total cost of tips: $C_{tiph} \times T_{cuttot} = C_{tiptot}$ (€)
Total cost of lenses: $C_{lensh} \times T_{cuttot} = C_{lenstot}$ (€)

Total cutting cost: $C_{labtot} + C_{elot} + C_{gastot} + C_{mhtot} + C_{tiptot} + C_{lenstot} = C_{tot}$ (€)

### 7.1.3 Oxyfuel

In addition to the variables from section 7.1, the following has to be taken into account to make a calculation regarding oxyfuel cutting:

$P_{fg}$ = price of fuel gas. (€/m³)
$P_{o}$ = price of oxygen. (€/m³)
$N_{pt}$ = number of parallel torches.
$T_{tip}$ = tip life. (h/tip)
$P_{tip}$ = tip price. (€/tip)
$C_{uts}$ = cutting speed. (m/min)
$T_{st}$ = time of cut start, penetration and movement. (s)
$C_{fg}$ = consumption of fuel gas. (l/h)
$C_{oco}$ = consumption of cutting oxygen. (l/h)
$C_{ho}$ = consumption of heating oxygen. (l/h)

If preheating is used the some variables specific to preheating are needed:

$P_{pg}$ = price of preheating gas. (€/m³)
$C_{pfg}$ = consumption of preheating gas. (l/h)
Tph = time of preheating. (min)

The total cost for an oxyfuel cutting job is given by:

Cost of cutting gases: \( \frac{P_{fg} \times Config + Po \times (Conco + Conho)}{1000} = C_{cgash} \) (€/h)

Number of machine hours per year: \( N_{op} \times N_{sh} \times U \times 0.01 = N_{opy} \) (h)
Cost of interest: \( P_{cap} \times Int \times 0.5 \times 0.01 = C_{int} \) (€/year)
Cost of depreciation: \( P_{cap} / T_{mach} = C_{dep} \) (€/year)
Cost of insurance: \( P_{cap} \times Ins \times 0.01 = C_{ins} \) (€/year)
Cost of space: \( S_{req} \times Prent \times 12 = C_{s} \) (€/year)
Cost of maintenance: \( P_{cap} \times Maint \times 0.01 = C_{maint} \) (€/year)
Rate per machine hour: \( \frac{C_{int} + C_{dep} + C_{ins} + C_{s} + C_{maint}}{N_{opy}} = R_{mh} \) (€/h)

Number of tips: \( \frac{1}{T_{tip}} = C_{tip} \) (tip/h)

Cost of tips: \( C_{tip} \times N_{pt} \times P_{tip} = C_{tiptot} \) (€)

Total cut length: \( L_{cutp} \times N_{p} = L_{cuttot} \) (m)
Total time of cut starts: \( \frac{N_{stp} \times T_{st} \times N_{p}}{3600} = T_{sttot} \) (h)
Total time of cutting: \( \frac{L_{cuttot} / (Cutsp \times 60) + T_{sttot}}{N_{pt}} = T_{cuttot} \) (h)

Total cost of labour: \( P_{lab} \times (T_{prep} + T_{cuttot}) = C_{labtot} \) (€)
Total cost of cutting gases: \( C_{cgash} \times T_{cuttot} = C_{cgastot} \) (€)
Total cost of machine hours: \( R_{mh} \times T_{cuttot} = C_{mhtot} \) (€)
Total cost of tips: \( C_{tip} \times T_{cuttot} = C_{tiptot} \) (€)

Total cutting cost: \( C_{labtot} + C_{cgastot} + C_{mhtot} + C_{tiptot} = C_{tot} \) (€)

If preheating is used then that cost is added to Ctot. The preheating is preformed either offline or online. The additional cost of offline preheating (Cphoff) is given by:

Cost of preheating gas: \( P_{pg} \times Conpg \times 1000 = C_{pg} \) (€/h)
Cost of offline preheating: \( (C_{pg} + P_{lab}) \times (T_{ph} / 60) = C_{phoff} \) (€)

The additional cost of online preheating (Cphon) is given by:

Cost of preheating gas: \( P_{pg} \times Conpg \times 1000 = C_{pg} \) (€/h)
Cost of offline preheating: \((C_{pgh} + P_{lab} + R_{mh}) \times \frac{T_{ph}}{60} = C_{phon} (€)\)

### 7.1.4 Plasma

In addition to the variables from section 7.1, the following has to be taken into account to make a calculation for plasma cutting:

- \(P_{pg}\) = price of plasma gas. (€/m³)
- \(P_{cg}\) = price of cooling gas. (€/m³)
- \(N_{pt}\) = number of parallel torches.
- \(T_{tip}\) = tip life. (h/tip)
- \(P_{tip}\) = tip price. (€/tip)
- \(T_{cat}\) = cathode life. (h/cat)
- \(P_{cat}\) = cathode price. (€/cat)
- \(C_{uts}\) = cutting speed. (m/min)
- \(T_{st}\) = time of cut start, penetration and movement. (s)
- \(C_{onplg}\) = consumption of fuel gas. (l/h)
- \(C_{concg}\) = consumption of cooling gas. (l/h)

The total cost \((C_{tot}, €)\) for a plasma cutting job is given by:

- Cost of gases: \(\frac{P_{pg} \times C_{onpg} + P_{cg} \times C_{concg}}{1000} = C_{gash} (€/h)\)
- Cost of electricity: \(E_{lp} \times E_{el} = C_{elh} (€/h)\)

Number of machine hours per year: \(N_{op} \times N_{sh} \times U \times 0.01 = N_{opy} (h)\)
- Cost of interest: \(P_{cap} \times I_{nt} \times 0.5 \times 0.01 = C_{int} (€/year)\)
- Cost of depreciation: \(P_{cap} / T_{mach} = C_{dep} (€/year)\)
- Cost of insurance: \(P_{cap} \times I_{ns} \times 0.01 = C_{ins} (€/year)\)
- Cost of space: \(S_{req} \times P_{rent} \times 12 = C_{s} (€/year)\)
- Cost of maintenance: \(P_{cap} \times M_{aint} \times 0.01 = C_{maint} (€/year)\)

Rate per machine hour: \(\frac{(C_{int} + C_{dep} + C_{ins} + C_{s} + C_{maint})}{N_{opy}} = R_{mh} (€/h)\)

Number of tips: \(\frac{1}{T_{tip}} = C_{onptip} (tip/h)\)
- Cost of tips: \(C_{onptip} \times N_{pt} \times P_{tip} = C_{tiph} (€/h)\)

Number of cathodes \(\frac{1}{T_{cat}} = C_{oncat} (cat/h)\)
- Cost of cathodes: \(C_{oncat} \times N_{pt} \times P_{cat} = C_{cath} (€/h)\)
Total cut length: \( \text{Lcutp} \times \text{Np} = \text{Lcuttot} \) (m)
Total time of cut starts: \( \frac{(\text{Nstp} \times \text{Tst} \times \text{Np})}{3600} = \text{Tsttot} \) (h)
Total time of cutting: \( \frac{(\text{Lcuttot} / (\text{Cutsp} \times 60) + \text{Tsttot})}{\text{Npt}} = \text{Tcuttot} \) (h)

Total cost of labour: \( \text{Plab} \times (\text{Tprep} + \text{Tcuttot}) = \text{Clabtot} \) (€)
Total cost of gases: \( \text{Cgash} \times \text{Tcuttot} = \text{Cgastot} \) (€)
Total cost of electricity: \( \text{Celh} \times \text{Tcuttot} = \text{Celtot} \) (€)
Total cost of machine hours: \( \text{Rmh} \times \text{Tcuttot} = \text{Cmhtot} \) (€)
Total cost of tips: \( \text{Ctiph} \times \text{Tcuttot} = \text{Ctiptot} \) (€)
Total cost of cathodes: \( \text{Ccath} \times \text{Tcuttot} = \text{Ccattot} \) (€)

Total cutting cost: \( \text{Clabtot} + \text{Cgastot} + \text{Celtot} + \text{Cmhtot} + \text{Ctiptot} + \text{Ccattot} = \text{Ctot} \) (€)

**7.2 Analysis**

Below are the analyses of some examples calculations that are made with the models described in section 7.1. For detailed information regarding the calculations see Appendix 2.

**7.2.1 Oxyfuel with and without preheating**

When comparing oxyfuel cutting with and without preheating it is found that it rather quickly becomes cheaper to use preheating. Cutting with reduced speed is only cheaper when the cut length of each part is very short or the batch is small. With thicker plates it becomes cheaper to use preheating more quickly.

**7.2.2 Cutting of HARDOX 600**

The calculations were made to see in which cases abrasive water jet cutting is a viable option. When comparing AWJ with the other cutting methods it is found that it is economically comparable with oxyfuel cutting with preheating when cutting small batches or in the case of short cut length per part. In addition, AWJ generally is more expensive than laser cutting and plasma cutting. However, AWJ is the only cutting method that leaves the cut edge unaffected by heat and the hardness and other properties of the steel unchanged.
8 Application structure

In this chapter a basic structure is laid out for an application of the kind discussed in the chapters 1 and 6. Focus is on the user interaction and the information that is displayed to the user.

First of all there should be a start screen where a number of options as to what the user wish to do is presented. There could be five main options:

- Cost calculation
- Recommended cutting speeds for SSAB’s steels
- Information regarding cutting methods
- Troubleshooting
- Configuration

8.1 Cost calculation

In this section of the application the user can make an extensive cost calculation and compare the result with results from other calculations. The calculations could be based upon the calculation models that are presented in chapter 7.1.

First the user should choose material and thickness that is to be cut and the desired cut quality. Based on that the user is given a choice of the suitable cutting methods.
After the selection of a cutting method some data has to be entered.

Choose cutting method → Enter necessary data

For example, number parts to be cut and the cut length per part. Other data, which don’t change between calculations, for example interest rate and labour cost, are taken from a set of default values. The user can, and should, edit the default values so that they reflect the local situation. This is discussed further in section 8.5. After the necessary data has been entered the cost is calculated.

The results can either be in the form of a number, for example total cost of a cutting job, or in the form of a graph. The user should be able to choose to vary any of the variables in the calculation to plot a graph, for example, cost per part on the y-axis and different batch sizes on the x-axis.

In addition, the user should be able to save the results from a calculation in a suitable format so that comparisons with other results can be done, for example, plot the results from different calculations in the same graph.

8.2 Recommended cutting speeds

In this section SSAB’s recommended cutting speeds are presented. After the user chooses material, thickness and cutting method, the recommended cutting speed is displayed. If oxyfuel cutting is chosen, both the reduced cutting speed and the full cutting speed, that can be used if the material is preheated, as well as the preheating temperature, is displayed.

8.3 Cutting methods

In this section of the application the different cutting methods are explained. The information could be more or less the same as that in chapter 2 of this report. Also, if considered appropriate, the contents of chapters 3 and 4 could also be presented in this section of the application.

8.4 Troubleshooting

SSAB already has some documents with pictures of cut edges and tips on how to improve the cut quality. If SSAB wants to it could be a good idea to further develop
this material and to extend it to incorporate more cutting methods and then include it in the application as a section on troubleshooting.

8.5 Configuration

In this section of the application the user should be able to set the default values of the variables used in the cost calculations that are considered not to change between different calculations. In addition, the user should be able to adjust other settings, for example, choose which currency to use in the calculations.

Using the calculation models described in chapter 7.1, the variables that are common for all the cutting methods are:

- Cost of labour
- Number of operating hours per year and shift
- Machine life expectancy, depreciation time
- Annual interest
- Insurance
- Rent
- Price of electricity

The default variables that have to be set specifically for abrasive water jet are:

- Machine life expectancy, depreciation time
- Required space
- Maintenance
- Time for preparation
- Electric power consumption
- Price of abrasive
- Tip life
- Tip price

The default variables that have to be set specifically for laser are:

- Machine life expectancy, depreciation time
- Required space
- Maintenance
- Time for preparation
- Electric power consumption
- Price of cutting gas
- Price of laser gas
- Tip life
- Tip price
- Lens life
- Lens price

The default variables that have to be set specifically for oxyfuel are:

- Machine life expectancy, depreciation time
- Required space
- Maintenance
- Time for preparation
- Price of fuel gas
- Price of oxygen
- Tip life
- Tip price
- Price of preheating gas

The default variables that have to be set specifically for plasma are:

- Machine life expectancy, depreciation time
- Required space
- Maintenance
- Time for preparation
- Electric power consumption
- Price of plasma gas
- Price of cooling gas
- Tip life
- Tip price
- Cathode life
- Cathode price
9 Conclusions and recommendations

It is possible to calculate the costs involved in the different cutting processes quite accurately. To calculate the costs involved in preheating before cutting with oxyfuel it is recommended to develop a more complex model. The model presented in this thesis is very limited and only valid for plates of steel that are 1 x 2 meters of size.

The recommendation is for SSAB to continue developing an application to help its customers calculate their cutting costs. It is also to use the application to influence customers to use cutting methods and cutting speeds that does not produce edge cracking. This would benefit both SSAB and its customers as it makes SSAB seem knowledgeable about the problems that the customers face and also help the customers to be more productive.
10 References

10.1 Books and reports

10.2 Personal contacts and interviews

Sonander, C. Applications Engineer, SSAB Oxelösund AB, Oxelösund. Personal communication, October 28, 2003.


Appendix 1: Preheating experiments

General comments

Sensor 1 shows the temperature on the top surface of the plate. However, since the temperature sensor is fastened to the plate using a magnet, the log output probably shows the rise and fall of the temperature in the magnet, as the flame passes over it, as shown in the picture below, rather than the temperature on the plate surface. The actual surface temperature is most likely considerably lower than the local low-points on that curve, judging from the rather steep rate of temperature decline before the flame passes again.

![Figure 1: Flames passing a sensor fastened using a magnet](image)

Sensor 2 shows the temperature on the bottom surface of the plate. However, since the steel plate conducts heat very well it is possible to approximate the temperature in the middle of the plate to be fairly close to the temperature at sensor 2. Thus, the output from sensor 2 was used as the steel temperature in the calculations.
Log outputs

The outputs from sensors 3 and 4 are very similar to those of sensors 1 and 2. Therefore, in order to make the presentation of the log outputs as understandable as possible, only the outputs from sensors 1 and 2 are showed in the plots below.
Experiments 1 and 2 were completed without any problems, with top temperatures at sensor 1 at around 350 °C. After experiment 3 was completed, concerns were raised regarding the relatively low top temperatures at around 250 °C, it was thought that perhaps some setting affecting the gas flow had been changed. This was even more evident during experiment 4 where, at first, top temperatures as low as around 150 to 200 °C were observed. Since this was discovered after about twenty minutes, the gas flow could be restored, and could during the rest of the experiment be kept at the same level as during experiments 1 and 2. This can clearly be seen in the log output from experiment 4. Because of these deviations, from experiment 4, only the log output from after twenty minutes was used in the calculations. Furthermore, the results from experiment 2 were not considered as gravely as the results from the other experiments.

Calculations

A heating process is non linear, however, in this very limited temperature interval the process can be approximated to be linear, as can be seen in the log outputs.

Since the heating process was approximated to be linear, two sets of values were chosen from each of the log outputs, in between which the plot was more or less a
straight line. Time was measured in seconds rather than in minutes, which is used in the plots to make them more understandable.

A simple linear model was chosen:

\[ y = k \times x + m \]

where \( y \) = preheat temperature (°C), \( k \) = heating factor, \( x \) = time (s) and \( m \) = start temperature (°C). And:

\[ k = \frac{\Delta \text{Temp}}{\Delta \text{Time}} \]

The chosen values were:

1, 80 mm:

\[ \begin{array}{ccc}
1000 \text{ s} & 86.1 \degree \text{C} & \Delta \text{Temp:} 86.5 \degree \text{C} \\
3000 \text{ s} & 172.6 \degree \text{C} & \Delta \text{Time:} 2000 \text{ s}
\end{array} \]

\[ k_1 = 0.0435 \degree \text{C/s} \]

2, 30 mm:

\[ \begin{array}{ccc}
500 \text{ s} & 72.9 \degree \text{C} & \Delta \text{Temp:} 99.7 \degree \text{C} \\
1500 \text{ s} & 172.6 \degree \text{C} & \Delta \text{Time:} 1000 \text{ s}
\end{array} \]

\[ k_2 = 0.0997 \degree \text{C/s} \]

3, 100 mm:

\[ \begin{array}{ccc}
1000 \text{ s} & 42.6 \degree \text{C} & \Delta \text{Temp:} 25.1 \degree \text{C} \\
2000 \text{ s} & 67.7 \degree \text{C} & \Delta \text{Time:} 1000 \text{ s}
\end{array} \]

\[ k_3 = 0.0251 \degree \text{C/s} \]

4, 60 mm:

\[ \begin{array}{ccc}
1500 \text{ s} & 59.4 \degree \text{C} & \Delta \text{Temp:} 76.6 \degree \text{C} \\
3000 \text{ s} & 136 \degree \text{C} & \Delta \text{Time:} 1500 \text{ s}
\end{array} \]

\[ k_4 = 0.0511 \degree \text{C/s} \]

To create a model for “\( k \)”, it was assumed that:

\[ k = \frac{r}{t} + s \]

where \( r \) = unknown 1, \( t \) = plate thickness (mm) and \( s \) = unknown 2.

Combining the different values of “\( k \)” and “\( t \)” did not give any good results, “\( s \)” ranged from -0.485 to 0.0207 and “\( r \)” from 1.824 to 42.18. In conclusion, “\( s \)” was neither positive nor negative but “\( r \)” was positive for all combinations.
A new model for “k” was created:

\[ k = \frac{r}{t} \]

where \( r \) = unknown and \( t \) = plate thickness (mm).

This model gave the results:

\[
\begin{align*}
    r_1 &= 3.480 \\
    r_2 &= 2.991 \\
    r_3 &= 2.510 \\
    r_4 &= 3.066
\end{align*}
\]

which are all fairly close to the value 3. If “r” is approximated to 3 the model for “y” would look like:

\[ y = \frac{3x}{t} + m \]

where \( y \) = preheat temperature (°C), \( x \) = time (s), \( t \) = plate thickness (mm) and \( m \) = start temperature (°C). When the lines between the chosen values of the plots were extrapolated to find where they crossed the y-axis it was found that this point were around 5 degrees higher than the actual starting temperature. Accordingly, the model was corrected:

\[ y = \frac{3x}{t} + m + 5 \]

Solved for “x” and using minutes for time:

\[ x = \frac{t(y - m - 5)}{180} \]

When this model was compared to the practical experiments it was shown to be fairly accurate. It was only a few seconds up to a few minutes off when compared to the outputs from the first two experiments. It was however more off when compared to the output from the third experiment, probably due to the low gas flow used in that experiment. Furthermore, it was very accurate when compared to the output from the forth experiment if the plot was extrapolated from the part after 20 minutes towards the y-axis, using a value of –20 °C as a starting temperature.
Appendix 2: Example calculations

The values below were used in all calculations if nothing else is specifically stated. All numbers are examples of possible default values. They were given by SSAB and were checked during the interviews, see section 6, to be suitable as values to base example calculations on.

Common for all cutting methods:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nstp</td>
<td>1</td>
<td>Number of cut starts per part</td>
</tr>
<tr>
<td>Nsh</td>
<td>1</td>
<td>Number of shifts</td>
</tr>
<tr>
<td>Plab</td>
<td>25</td>
<td>Cost of labour (€/h)</td>
</tr>
<tr>
<td>Pel</td>
<td>0,14</td>
<td>Price of electricity (€/kWh)</td>
</tr>
<tr>
<td>Nop</td>
<td>1450</td>
<td>Number of operating hours per year and shift (h)</td>
</tr>
<tr>
<td>Tmash</td>
<td>10</td>
<td>Machine life time expectancy (years)</td>
</tr>
<tr>
<td>Int</td>
<td>5</td>
<td>Interest (% per year)</td>
</tr>
<tr>
<td>Ins</td>
<td>2,5</td>
<td>Insurance (% of Pcap per year)</td>
</tr>
<tr>
<td>Sreq</td>
<td>80</td>
<td>Required space (m²)</td>
</tr>
<tr>
<td>Prent</td>
<td>4</td>
<td>Rent (€/m² * month)</td>
</tr>
<tr>
<td>Maint</td>
<td>2</td>
<td>Maintenance (% of Pcap per year)</td>
</tr>
<tr>
<td>Tprep</td>
<td>1</td>
<td>Time for preparation, NC-programming etc. (h)</td>
</tr>
</tbody>
</table>

Abrasive water jet:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pcap</td>
<td>150000</td>
<td>Capital (€)</td>
</tr>
<tr>
<td>U</td>
<td>80</td>
<td>Utilisation (% of Nop)</td>
</tr>
<tr>
<td>Pab</td>
<td>0,25</td>
<td>Price of abrasive (€/kg)</td>
</tr>
<tr>
<td>Ttip</td>
<td>100</td>
<td>Tip life (h/tip)</td>
</tr>
<tr>
<td>Ptip</td>
<td>100</td>
<td>Price per tip (€)</td>
</tr>
<tr>
<td>Elp</td>
<td>20</td>
<td>Electrical power consumption (kW)</td>
</tr>
</tbody>
</table>

Laser:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pcap</td>
<td>380000</td>
<td>Capital (€)</td>
</tr>
<tr>
<td>U</td>
<td>80</td>
<td>Utilisation (% of Nop)</td>
</tr>
<tr>
<td>Pcgas</td>
<td>1</td>
<td>Price of cutting gas (€/m³)</td>
</tr>
<tr>
<td>Plgas</td>
<td>20</td>
<td>Price of laser gas (€/m3)</td>
</tr>
<tr>
<td>Ttip</td>
<td>1000</td>
<td>Tip life (h/tip)</td>
</tr>
<tr>
<td>Code</td>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>155</td>
<td>Ptip</td>
<td>Price per tip (€)</td>
</tr>
<tr>
<td>1000</td>
<td>Tlens</td>
<td>Lens life (h/lens)</td>
</tr>
<tr>
<td>770</td>
<td>Plens</td>
<td>Price per lens (€)</td>
</tr>
</tbody>
</table>

**Oxyfuel:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>50000</td>
<td>Pcap</td>
<td>Capital (€)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Npt</td>
<td>Number of parallel torches</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>U</td>
<td>Utilisation (% of Nop)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pfg</td>
<td>Price of fuel gas (€/m³)</td>
<td></td>
</tr>
<tr>
<td>1,5</td>
<td>Po</td>
<td>Price of oxygen (€/m³)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Ppg</td>
<td>Price of preheating gas (€/m³)</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Ttip</td>
<td>Tip life (h/tip)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Ptip</td>
<td>Price per tip (€)</td>
<td></td>
</tr>
</tbody>
</table>

**Plasma:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>U</td>
<td>Utilisation (% av Nop)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Ppg</td>
<td>Price of plasma gas (€/m³)</td>
<td></td>
</tr>
<tr>
<td>0,01</td>
<td>Pcg</td>
<td>Price of cooling gas (€/m³)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Npt</td>
<td>Number of parallel torches</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Ttip</td>
<td>Tip life (h/tip)</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Ptip</td>
<td>Price per tip (€)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Tcat</td>
<td>Cathode life (h/tip)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Pcat</td>
<td>Price per cathode (€)</td>
<td></td>
</tr>
</tbody>
</table>
Oxyfuel with and without preheating

Material thickness 30 mm

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Tst</td>
<td>Time of cut start, penetration and movement (s)</td>
</tr>
<tr>
<td>450</td>
<td>Config</td>
<td>Consumption of fuel gas (l/h)</td>
</tr>
<tr>
<td>4000</td>
<td>Conco</td>
<td>Consumption of cutting oxygen (l/h)</td>
</tr>
<tr>
<td>600</td>
<td>Conho</td>
<td>Consumption of heating oxygen (l/h)</td>
</tr>
<tr>
<td>5000</td>
<td>Conpg</td>
<td>Consumption of preheating gas (l/h)</td>
</tr>
</tbody>
</table>

Oxyfuel without preheating

0,25 | Cutspeed | Cutting speed (m/min)

Oxyfuel with online preheating

0,50 | Cutspeed | Cutting speed (m/min)
| 30 | t | Plate thickness (mm) |
| 100 | y | Preheat temperature (°C) |
| 20 | m | Start temperature (°C) |

30mm Np=30

<table>
<thead>
<tr>
<th>Lcutp (m)</th>
<th>w/</th>
<th>w/o</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,4</td>
<td>1,58</td>
<td>1,43</td>
</tr>
<tr>
<td>0,5</td>
<td>1,65</td>
<td>1,55</td>
</tr>
<tr>
<td>0,6</td>
<td>1,73</td>
<td>1,68</td>
</tr>
<tr>
<td>0,7</td>
<td>1,8</td>
<td>1,8</td>
</tr>
<tr>
<td>0,8</td>
<td>1,88</td>
<td>1,92</td>
</tr>
<tr>
<td>0,9</td>
<td>1,95</td>
<td>2,04</td>
</tr>
<tr>
<td>1</td>
<td>2,03</td>
<td>2,16</td>
</tr>
</tbody>
</table>

Price per part (€)

30mm Np=30

Price per part (€) vs. Lcutp (m)
30mm Np=50

<table>
<thead>
<tr>
<th>Lcutp</th>
<th>0,1</th>
<th>0,2</th>
<th>0,3</th>
<th>0,4</th>
<th>0,5</th>
<th>0,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/</td>
<td>0,96</td>
<td>1,04</td>
<td>1,11</td>
<td>1,19</td>
<td>1,26</td>
<td></td>
</tr>
<tr>
<td>w/o</td>
<td>0,86</td>
<td>0,98</td>
<td>1,1</td>
<td>1,22</td>
<td>1,34</td>
<td></td>
</tr>
</tbody>
</table>

30mm Np=100

<table>
<thead>
<tr>
<th>Lcutp</th>
<th>0,1</th>
<th>0,2</th>
<th>0,3</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/</td>
<td>0,54</td>
<td>0,61</td>
<td>0,69</td>
</tr>
<tr>
<td>w/o</td>
<td>0,48</td>
<td>0,61</td>
<td>0,73</td>
</tr>
</tbody>
</table>
Material thickness 50 mm

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Tst</td>
<td>Time of cut start, penetration and movement (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>Config</td>
<td>Consumption of fuel gas (l/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>Conco</td>
<td>Consumption of cutting oxygen (l/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>Conho</td>
<td>Consumption of heating oxygen (l/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>Conpg</td>
<td>Consumption of preheating gas (l/h)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Oxyfuel without preheating

0,15  Cutsp  Cutting speed (m/min)

Oxyfuel with online preheating

0,37  Cutsp  Cutting speed (m/min)

50  t  Plate thickness (mm)

150  y  Preheat temperature (°C)

20  m  Start temperature (°C)

50mm Np=30

Lcutp: 0,4  0,5  0,6  0,7  0,8
w/ 2,3  2,4  2,51  2,61  2,72
w/o 2,01  2,27  2,53  2,79  3,05

![Graph](image-url)
50mm Np=50
Lcutp: 0,2  0,3  0,4  0,5
w/  1,39  1,49  1,6  1,71
w/o  1,15  1,41  1,67  1,93

50mm Np=100
Lcutp: 0,1  0,2  0,3
w/  0,76  0,86  0,97
w/o  0,64  0,9  1,16
Cutting of HARDOX 600

Some of the variables used in the calculations are specific to a certain material and material thickness. The values used are presented with the results below.

Material thickness 12 mm

**AWJ**

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td></td>
<td>Conab Consumption of abrasive (kg/h)</td>
</tr>
<tr>
<td>0,2</td>
<td></td>
<td>Cutsp Cutting speed (m/min)</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Tst Time of cut start, penetration and movement (s)</td>
</tr>
</tbody>
</table>

**Laser**

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td></td>
<td>Elp Electrical power consumption (kW)</td>
</tr>
<tr>
<td>1,5</td>
<td></td>
<td>Cutsp Cutting speed (m/min)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Tst Time of cut start, penetration and movement (s)</td>
</tr>
<tr>
<td>3100</td>
<td></td>
<td>Concgas Consumption of cutting gas (l/h)</td>
</tr>
<tr>
<td>250</td>
<td></td>
<td>Conlgas Consumption of laser gas (l/h)</td>
</tr>
</tbody>
</table>

**Oxyfuel with online preheating**

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,7</td>
<td></td>
<td>Cutsp Cutting speed (m/min)</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Tst Time of cut start, penetration and movement (s)</td>
</tr>
<tr>
<td>400</td>
<td></td>
<td>Config Consumption of fuel gas (l/h)</td>
</tr>
<tr>
<td>1500</td>
<td></td>
<td>Conco Consumption of cutting oxygen (l/h)</td>
</tr>
<tr>
<td>500</td>
<td></td>
<td>Conho Consumption of heating oxygen (l/h)</td>
</tr>
<tr>
<td>5000</td>
<td></td>
<td>Conpg Consumption of preheating gas (l/h)</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>t Plate thickness (mm)</td>
</tr>
<tr>
<td>175</td>
<td></td>
<td>y Preheat temperature (°C)</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>m Start temperature (°C)</td>
</tr>
</tbody>
</table>

**Plasma**

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,5</td>
<td></td>
<td>Cutsp Cutting speed (m/min)</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Tst Time of cut start, penetration and movement (s)</td>
</tr>
<tr>
<td>2040</td>
<td></td>
<td>Conpg Consumption of plasma gas (l/h)</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>Concg Consumption of cooling gas (l/h)</td>
</tr>
<tr>
<td>54</td>
<td></td>
<td>Elp Electrical power consumption (kW)</td>
</tr>
<tr>
<td>Material</td>
<td>Cost per part</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>AWJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxyfuel w/preheat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**H600 12mm Lcutp=0,5m**

<table>
<thead>
<tr>
<th>Np</th>
<th>AWJ</th>
<th>Laser</th>
<th>Oxyfuel w/preheat</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>15,80</td>
<td>13,13</td>
<td>17,03</td>
<td>12,76</td>
</tr>
<tr>
<td>50</td>
<td>5,8</td>
<td>3,13</td>
<td>3,89</td>
<td>2,76</td>
</tr>
<tr>
<td>100</td>
<td>3,8</td>
<td>1,13</td>
<td>1,26</td>
<td>0,76</td>
</tr>
</tbody>
</table>

**H600 12mm Np=10 Lcutp=var**

<table>
<thead>
<tr>
<th>Lcutp</th>
<th>AWJ</th>
<th>Laser</th>
<th>Oxyfuel w/preheat</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,5</td>
<td>3,4</td>
<td>2,69</td>
<td>3,5</td>
<td>2,6</td>
</tr>
<tr>
<td>1</td>
<td>5,8</td>
<td>3,13</td>
<td>3,89</td>
<td>2,76</td>
</tr>
<tr>
<td>2</td>
<td>8,79</td>
<td>3,68</td>
<td>4,38</td>
<td>2,95</td>
</tr>
</tbody>
</table>

**H600 12mm Np=10**

<table>
<thead>
<tr>
<th>Lcutp</th>
<th>AWJ</th>
<th>Laser</th>
<th>Oxyfuel w/preheat</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,1</td>
<td>2,6</td>
<td>2,69</td>
<td>3,5</td>
<td>2,6</td>
</tr>
<tr>
<td>0,5</td>
<td>2,95</td>
<td>3,13</td>
<td>3,89</td>
<td>2,76</td>
</tr>
<tr>
<td>1</td>
<td>3,34</td>
<td>3,68</td>
<td>4,38</td>
<td>2,95</td>
</tr>
<tr>
<td>2</td>
<td>14,79</td>
<td>4,78</td>
<td>5,36</td>
<td>3,34</td>
</tr>
</tbody>
</table>
Material thickness 20 mm

AWJ
31 Conab Consumption of abrasive (kg/h)
0,08 Cutsp Cutting speed (m/min)
18 Tst Time of cut start, penetration and movement (s)

Laser
52 Elp Electrical power consumption (kW)
0,9 Cutsp Cutting speed (m/min)
4 Tst Time of cut start, penetration and movement (s)
4000 Concgas Consumption of cutting gas (l/h)
330 Conlgas Consumption of laser gas (l/h)

Oxyfuel with online preheating
0,6 Cutsp Cutting speed (m/min)
14 Tst Time of cut start, penetration and movement (s)
450 Config Consumption of fuel gas (l/h)
2500 Conco Consumption of cutting oxygen (l/h)
600 Conho Consumption of heating oxygen (l/h)
5000 Conpg Consumption of preheating gas (l/h)
20 t Plate thickness (mm)
175 y Preheat temperature (°C)
20 m Start temperature (°C)

Plasma
1,6 Cutsp Cutting speed (m/min)
4 Tst Time of cut start, penetration and movement (s)
2040 Conpg Consumption of plasma gas (l/h)
0 Concg Consumption of cooling gas (l/h)
64 Elp Electrical power consumption (kW)
H600 20mm Lcutp=0,5m Np=var

<table>
<thead>
<tr>
<th></th>
<th>AWJ</th>
<th>Laser</th>
<th>Oxyfuel w/preheat</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20,38</td>
<td>13,57</td>
<td>19,81</td>
<td>12,88</td>
</tr>
<tr>
<td>10</td>
<td>10,38</td>
<td>3,57</td>
<td>4,57</td>
<td>2,88</td>
</tr>
<tr>
<td>50</td>
<td>8,38</td>
<td>1,57</td>
<td>1,53</td>
<td>0,88</td>
</tr>
<tr>
<td>100</td>
<td>8,13</td>
<td>1,32</td>
<td>1,14</td>
<td>0,63</td>
</tr>
</tbody>
</table>

H600 20mm Np=10 Lcutp=var

<table>
<thead>
<tr>
<th></th>
<th>AWJ</th>
<th>Laser</th>
<th>Oxyfuel w/preheat</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,1</td>
<td>4,36</td>
<td>2,81</td>
<td>4,1</td>
<td>2,63</td>
</tr>
<tr>
<td>0,5</td>
<td>10,38</td>
<td>3,57</td>
<td>4,57</td>
<td>2,88</td>
</tr>
<tr>
<td>1</td>
<td>17,9</td>
<td>4,52</td>
<td>5,17</td>
<td>3,19</td>
</tr>
<tr>
<td>2</td>
<td>32,94</td>
<td>6,43</td>
<td>6,36</td>
<td>3,81</td>
</tr>
</tbody>
</table>

H600 20mm Lcutp=0,5m

- AWJ
- Laser
- Oxyfuel w/preheat
- Plasma

H600 20mm Np=10

- AWJ
- Laser
- Oxyfuel w/preheat
- Plasma