Manufacturing sustainability and reengineering analysis of a crane boom member

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Luleå, June 2009
Preface

I would like to express my sincere gratitude to my Thesis supervisor Torbjörn Ilar, teacher of the Division of Manufacturing Systems Engineering, Luleå Tekniska Universitet, Sweden, for his patience and dedication during all the time that I have been carrying out this Thesis.

I also want to express my gratitude to Gustavo Peláez, teacher of the Universidade de Vigo and my supervisor in Spain. I am grateful for his advices.

I can not forget to be grateful with my laboratory mate, Benxa. Who shared with me this Swedish experience.

I would like to thank my friends of Luleå and Galicia; all of you have been made all these years the greatest years of my life.

Finally and specially, I wish to thank my family and my girlfriend, Maria, you always have trusted me.

Germán Rúa Collazo

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Abstract

Nowadays the demands of the society force companies producing cranes to employ high productivity fabrication techniques and to design them with reduced weight and optimum structural integrity. The possible measures for this are to introduce high strength materials, to apply weld and/or surface improvement technologies and to utilise high productivity manufacturing technologies. High-strength materials enable allowable stress levels to be increased and section thickness reduced accordingly.

The main objective in this master’s thesis is to know the benefits obtained due to reconsidered design of the crane’s members. This process consists in three basic aspects:

- Change material, from Domex 900 to Weldox 1100.
- Reduce thickness, from 6 mm to 4 mm.
- Change welding method, from TIG to Laser-MIG and from one weld to two welds.

To explain this, the elaboration method of a crane member (3 m of length, 0.4 m of height and 0.2 m of width) has been studied, since the steel sheets are received until the member is ready to work like a crane component. All the steps are explained in this report.

At the end, the economical benefits for the final customers are studied.
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1. Introduction

1.1. Background

The development of new generations of transport equipment means, in general, increased capacity, speed and demands on service life. For cranes, excavators and similar equipment with modern hydraulic systems the number of fatigue cycles per operating hour will increase due to reduced cycle time.

Advantages are not achieved simply by substituting a lower strength material for a higher strength one, but rather the entire design of the structures must be re-considered. Higher strength material has significant potential for both weight savings and reduced manufacturing costs. Higher strength material will generally allow for thinner cross sections and less material. This in turn, reduces all aspects of production costs from material handling to cutting, edge preparation and welding cost. Greater implementation of new materials, like high strength and high wear resistance steels, however, requires than more attention be given to detail design and manufacturing quality. Innovative new design will require that a system be established for making use of higher quality welds at the design phase.
1.2. Domex

Domex is the brand name of hot-rolled sheet steel from SSAB Tunnplåt. Domex advanced high strength steels (AHSS) are supplied in the thickness range of 2–12 mm. Due to the very good formability in cold state these steels are also known as cold-forming steels. Domex AHSS are characterized by high yield strength, excellent formability and good weldability. Domex AHSS are very often used in the transportation industry (trailers, trucks, tippers, automotive, train). Domex AHSS are available in the yield strength levels shown in figure 1.

![Figure 1: Strength of Domex AHSS](image)

In this master’s thesis, Domex 900 is studied.

The entire range extends from Domex MC cold-forming steels to wear-resistant or corrosion resistant steels, as well as ballistic protection sheet steel and electrical sheet steel.

Fusion welding of Domex AHSS has been employed for many years and does not differ significantly from fusion welding of mild steels. In order to reap the benefits of these high strength steels, the welding process must be controlled in a suitable manner.

All Domex AHSS are produced in modern plants under strict process control. The steels are micro-alloyed with niobium, titanium and vanadium, which enables low carbon and manganese contents to be maintained. The steels are produced by metallurgical
processes that ensure very high purity of the steels, and they are then finished in a carefully controlled thermomechanical rolling process that ensures consistent properties.

Domex AHSS are characterised by:

- Excellent formability in relation to their high strength.
- Good weldability due to their low contents of alloying elements.
- Good impact strength at low temperatures, which should be specified at the time of ordering.
- Suitable for laser cutting.
- Suitable for hot-dip galvanising due to their appropriately formulated chemical composition. The order should specify that the steel will be hot-dip galvanised.

Domex AHSS are modern low-alloy structural steels for cold forming. Domex AHSS is available in nine steel grades, with grade designations corresponding to the minimum yield strength in the direction of rolling, ranging from 460 N/mm² up to 1200 N/mm². Domex AHSS meets the requirements of the EN 10149-2 standard, and is also guaranteed to allow for tighter minimum bending radii.

Domex AHSS has a high yield strength/tensile strength relationship. The steel has high internal purity and can be bent both along and across the direction of rolling, with minimum radii shown in a table.

**Domex 900**

Domex 900 is a thermomechanical rolled ultra high strength steel with a minimum yield strength of 900 MPa.

Domex 900 is developed with weight sensitive load carrying structures in mind. The material shows its true value in applications where the strength of the material can be used to increase the payload, or reduce the weight of the application itself, for instance cranes, lifting devices, chassis and equipment for heavy vehicles and other structures having very high demands on low weight. The data sheet of Domex 900 is attached.\textsuperscript{2,15}
1.3. Weldox

SSAB Oxelösund produces structural steels that conform to most international and national standards. Their extra-high strength structural steels are marketed under the Weldox brand name.

Weldox has been developed to provide excellent weldability, combined with high strength and toughness. The ore-based metallurgy and advanced processing in the steel shop ensures very low contents of residual elements in the steel. Weldox structural steels have excellent bendability and machinability properties. Due to the high strength of the steel, the end products can be strong but lightweight, which allows for substantial reductions in the cost of materials, welding and transport. Alternatively, if the weight is retained the product features can be enhanced; for example, extending a telescopic boom, increasing the carrying capacity or reducing the number of axles on a mobile crane.

Other distinguishing features of Weldox plate are closer thickness tolerances, higher surface quality and improved flatness. Closer thickness tolerances entail more precise weight calculations than with others steels, this enables to utilize the material more economically and reduce the safety margins. Thanks to the higher surface quality, a better surface finish is achieved. And finally, the improved flatness reduces the need to flatten and clamp the plate prior to welding and cutting.

Weldox structural steel plate is produced in thicknesses ranging from 4 to 130 mm, and with guaranteed yield strengths between 700 MPa and up to 1300 MPa. The flexible production system enables SSAB to deliver plate with tailored properties to suit the customer’s requirements. They can supply plate in thermomechanically rolled or quenched and tempered condition. In addition, most steels can be supplied with guaranteed impact toughness at temperatures down to –60°C.

Weldox is the world’s leading high-strength structural steel. Among other accomplishments, they were the first in the world to introduce structural steel with a yield strength of 1100 MPa. Their steel also has the market’s recognized highest and most uniform quality. That steel will be studied in this master’s thesis, Weldox 1100.

Weldox 1100

This is a general structural steel with a minimum yield strength of 1100 MPa. Its main application is load carrying structures having very high demands on weight. Will be used a sheet of 4 mm of thickness, what it carries a tensile strength of 1250 MPa. The data sheet of this steel is attached.\(^2\)\(^,\)\(^15\)
2. Raw material

2.1. Delivery condition

The following table shows the ranges which SSAB delivers the metal:

<table>
<thead>
<tr>
<th></th>
<th>Domex 900</th>
<th>Weldox 1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness mm</td>
<td>4´00 – 6´00</td>
<td>3´7 – 4´7</td>
</tr>
<tr>
<td>Width mm</td>
<td>990 – 1110</td>
<td>1000 – 2300</td>
</tr>
<tr>
<td>Length mm</td>
<td>1500 - 13000</td>
<td>2000 - 14500</td>
</tr>
</tbody>
</table>

Table 1. Delivery condition

As the dimensions of the final part are known, the dimensions of the blanks have to be calculated. That is carried out in the next section.
2.2. Blanks size

The dimensions of the section of the final part are 0.4 m of height and 0.2 m of width. In the case of the current steel, Domex 900, one sheet is used and one weld is executed. For the steel of the desired part, Weldox 1100, two sheets are used and also two welds are executed.

To calculate the dimensions of the blanks, it is necessary consider the flat zones plus the bends, as the following equations show:

Figure 2. Dimensions of the final part.
\[ L = A + B + \nu \]

\[ \nu = \pi \cdot \left( \frac{180 - \beta}{180} \right) \cdot \left( Ri + \frac{t}{2} \cdot k \right) - 2 \cdot (Ri + t) \cdot \tan \left( \frac{180 - \beta}{2} \right) \]

Where:

- \( \beta \) – angle bend
- \( Ri \) – bending radius
- \( t \) – sheet thickness
- \( k \) – deviation of the position of the neutral line

<table>
<thead>
<tr>
<th></th>
<th>Domex 900</th>
<th>Weldox 1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>( Ri )</td>
<td>13.2</td>
<td>14</td>
</tr>
<tr>
<td>( t )</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>( k )</td>
<td>0.82</td>
<td>0.92</td>
</tr>
<tr>
<td>( \nu )</td>
<td>-5.77</td>
<td>-4.20</td>
</tr>
</tbody>
</table>

Table 2. Steels parameters.

As it was mentioned before, the Domex part consists of one sheet, this means six flat zones and five bends. The width of that sheet is:

\[ L_{34} = A + B + \nu = 251.23 \text{ mm} \]

\[ L_{34-78} = L_{34} + L_{78} = 251.23 + 251.23 = 502.46 \text{ mm} \]

\[ L_{12-56} = L_{34-78} \]

\[ \text{Width}_D = L_{34-78} + L_{12-56} + \nu = 999.15 \text{ mm} \]

The Weldox part consists of two sheets, this means four flat zones and three bends per sheet. The width of one sheet is:

\[ L_{34} = A + B + \nu = 252.80 \text{ mm} \]

\[ L_{12} = L_{34} = 252.80 \text{ mm} \]

\[ \text{Width}_W = L_{12} + L_{34} + \nu = 501.40 \text{ mm} \]
2.3. Blanks weight

From the widths of the previous sections, the weights of the sheets are calculated. For this, an “extra-width” is considered due to the sheets will be cut by laser to obtain a better edge quality

\[ \text{Weight} = \text{density} \cdot \text{volume} \]

\[ \text{DomexWeight} = 7850 \text{kg/m}^3 \cdot (3000 \text{mm} \cdot 1001 \text{mm} \cdot 6 \text{mm}) \cdot \frac{1 \text{m}^3}{1000^3 \text{mm}^3} = 14144 \text{kg/part} \]

\[ \text{WeldoxWeight} = 2 \text{sheet} \left[ 7850 \text{kg/m}^3 \cdot (3000 \text{mm} \cdot 503 \text{mm} \cdot 4 \text{mm}) \cdot \frac{1 \text{m}^3}{1000^3 \text{mm}^3} \right] = 9476 \text{kg/part} \]
2.4 Blanks cost

From the weight of the blanks, the price of metal per part can be calculated as follow:

Domex Price = 2500 €/t = 2.5 €/kg

Weldox Price = 3000 €/t = 3 €/kg

\[
\text{DomexCost} = \frac{14144\text{kg} \cdot 2.5\text{€}}{\text{part}} = 3536\text{€} / \text{part}
\]

\[
\text{WeldoxCost} = \frac{9476\text{kg} \cdot 3\text{€}}{\text{part}} = 28428\text{€} / \text{part}
\]
3. Laser cutting

3.1. Laser cutting process

CO₂ and Nd:YAG are the main types of industrial cutting lasers. For CO₂ lasers the wavelength of infrared light produced is 10.6 µm and 1.06 µm for Nd:YAG lasers. The cut is produced by focusing a monochromatic light beam to a very small spot size by lenses and mirrors. Normally the power density is over 105 W/mm² and it’s enough to locally melt or vaporize the most materials. Once a through thickness zone of molten or vaporized 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 both 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 CO₂ lasers on the other hand is transmitted to the work piece by mirrors or transmissive optics. Because of this, CO₂ 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 CO₂ 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 oxidize 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 oxidized 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 utilizes 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. \(^8\)

![Figure 3. Laser cutting head](image)
3.2 Cost calculation

To cut the sheets a laser process is utilized, basically to avoid the joint preparation. Following the cost of the process is calculated:

Price of cutting gas, $P_{GC} = 1 \, \text{€/m}^3$
Price of laser gas, $P_{GL} = 20 \, \text{€/m}^3$

Consumption of cutting gas,
- $CG_C$ Domex = 2425 l/h
- $CG_C$ Weldox = 2200 l/h

Consumption of laser gas,
- $CG_L$ Domex = 190 l/h
- $CG_L$ Weldox = 170 l/h

Cost of gases,
\[
CG_{DOMEX} = \frac{(CG_C \cdot P_{GC} + CG_L \cdot P_{GL})}{1000} = 6'22\, \text{€/h}
\]
\[
CG_{WELDOX} = \frac{(CG_C \cdot P_{GC} + CG_L \cdot P_{GL})}{1000} = 5'6\, \text{€/h}
\]

Electrical power consumption,
- $PC_{DOMEX} = 35'5 \, \text{kW}$
- $PC_{WELDOX} = 32 \, \text{kW}$

Price of electricity,
- $PE = 0'0799 \, \text{€/kWh}$

Number of cut starts per part,
- $NS_{DOMEX} = 9$
- $NS_{WELDOX} = 2$

Perimeter of the holes,
\[
P = \pi \cdot \text{diameter} = \pi \cdot 100 = 314'15 \, \text{mm}
\]
Length of cut per part,

\[ \text{LC}_{\text{DOMEX}} = 2 \cdot 3000 + 2 \cdot 999^{15} + 8 \cdot 314^{15} = 10511^{15} \text{ mm} \]
\[ \text{LC}_{\text{WELDOX}} = 2 \cdot [2 \cdot (3000 - (8 \cdot 100)) + 2 \cdot 501^{40} + 4 \cdot 314^{15}] = 13318^{18} \text{ mm} \]

Price of labour,
\[ \text{PL} = 12 \text{ €/h} \]

Efficiency,
\[ \eta = 80\% \]

Speed of cutting,
\[ \text{SC}_{\text{DOMEX}} = 2 \text{ m/min} = 33^{33} \text{ mm/s} \]
\[ \text{SC}_{\text{WELDOX}} = 2 \text{ m/min} = 33^{33} \text{ mm/s} \]
The speed is also the same in both cases, because although Weldox is stronger is also thinner.

Time for preparation, TP is not taken in account. While one part is cut, another part is fixed in a contiguous table.

Time of cut Start, penetration and movement,
\[ \text{TM}_{\text{DOMEX}} = 2^{25} \text{ s} \]
\[ \text{TM}_{\text{WELDOX}} = 2^{25} \text{ s} \]
Total time of cuts starts,

\[ TS_{DOMEX} = NS \cdot TM = 9 \cdot 2'25 = 20'25s \]

\[ TS_{WELDOX} = NS \cdot TM = 2 \cdot 2'25 = 4'50s \]

Total time of cutting,

\[ TC_{DOMEX} = \frac{LC_{DOMEX}}{SC_{DOMEX}} \cdot \frac{1}{\eta} + TS_{DOMEX} = 419'53s = 0'1165h \]

\[ TC_{WELDOX} = \frac{LC_{WELDOX}}{SC_{WELDOX}} \cdot \frac{1}{\eta} + TS_{WELDOX} = 505'13s = 0'1403h \]

Total cost of labour,

\[ CL_{DOMEX} = PL \cdot TC_{DOMEX} = 1'40€ / part \]

\[ CL_{WELDOX} = PL \cdot TC_{WELDOX} = 1'68€ / part \]

Total cost of electricity,

\[ CE_{DOMEX} = PC_{DOMEX} \cdot PE \cdot TC_{DOMEX} = 0'33€ / part \]

\[ CE_{WELDOX} = PC_{WELDOX} \cdot PE \cdot TC_{WELDOX} = 0'36€ / part \]

Total cost of gases,

\[ TCG_{DOMEX} = CG_{DOMEX} \cdot TC_{DOMEX} = 0'72€ / part \]

\[ TCG_{WELDOX} = CG_{WELDOX} \cdot TC_{WELDOX} = 0'79€ / part \]
Total cost of the Cutting Process,

\[ TCG_{DOMEX} = CL_{DOMEX} + CE_{DOMEX} + TCG_{DOMEX} = 2'45\€ / part \]

\[ TCG_{WELDOX} = CL_{WELDOX} + CE_{WELDOX} + TCG_{WELDOX} = 2'83\€ / part \]
4. Bending

4.1. Bending process

Bending is the molding of sheet or strip metal, where angled or ring-shaped workpieces are produced. In bending, the plastic state is brought about by a bending load.

Bending is used as a sheet metal forming process to produce, among others, angled parts, sheet profiles, tubes or rings for various fields of application.

The bending results are dependent on a number of factors which we have grouped here under three headings: the plate, the tools and the procedure. ²

The plate

- **Steel grade**
  The bending force and springback increase with the plate strength. Typical tensile strength values are showed in the following table:

<table>
<thead>
<tr>
<th>Tensile strength $R_m$ [MPa]</th>
<th>Elongation $A_5$ [%]</th>
<th>Hardness [HBW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOMEX 900</td>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>WELDOX 1100</td>
<td>1440</td>
<td>11</td>
</tr>
</tbody>
</table>

  Table 3. Typical physical properties.

  So the stronger and harder the plate,
  – the higher the necessary bending force
  – the greater will be the springback
  – the larger the punch radius needed
  – the larger the punch radius needed

- **Plate surface**
  If the plate has a clean rolling surface, may be effected a more severe bending than with shotblasted and anti-corrosion painted plate. Surface damage and rust on the side of the plate which is under tension during bending may greatly reduce the bendability. In critical cases, such defects must be ground away.

- **Plate edges**
  Cut and sheared edges should be deburred and rounded with a grinder.

- **Plate thickness ($t$)**
  As a general rule, thinner plate can be bent to smaller radii without cracking.

- **Direction of rolling of the plate**
  The plate can be bent to a smaller radius at right angles to the direction of rolling than in the direction of rolling. See Figure 5.
Bend length (b)
If the bend length (see Figure 5) is less than 10 times the plate thickness, the plate can often be bent to a smaller radius.

The Tools
Punch radius (R)
The right punch radius is the most important factor when bending Domex and Weldox. (See Figure 3).
For the softer steels a punch radius which is equal to or somewhat smaller than the required bending radius is recommended. For stronger steels (Domex 900 and Weldox 1100), a punch radius which is equal to or somewhat larger than the required bending radius is recommended.

Die opening width (W)
It is recommended to use a minimum die opening for minimizing the springback. If the width is increased, the bending force and impression marks will admittedly be reduced, but at the expense of increased springback. Note that the opening angle must be so small that it will allow a sufficient amount of over-bending.

Bending procedure
Friction
The die edges must be clean and undamaged. The bending force needed and the risk of cracking can be reduced by using round rods free to rotate as die edges and/or by lubricating the die edges.

Bending angle
Note that the bending angle has a lesser effect on the force needed and the springback than the die opening width and steel grade. Springback can be compensated by over-bending by the same number of degrees.

Bending force (P)
The bending force necessary can be estimated using the formula below. The force is obtained in tonnes (1 tonne corresponds to 10 kN), with an accuracy of ±20%, provided that all dimensions used are in mm. For symbols used, see Figure 3.

\[ P = \frac{16 \cdot b \cdot t^2 \cdot R_m}{10000 \cdot W} \]

In the section 4.3., the Bending procedure is calculated.
4.2. Different kind of bending process

**Air bending**
In air bending, the tooling, punch and die, are used only to convey energy. The workpiece rests on two points. The punch carries out the bending movement. A curvature sets in, growing in the centre. Air bending is used mainly to straighten workpieces.

**Die bending**
In die bending, the bending punch presses the workpiece into the bending die. The deformation ends with a localized compressive stress in the die. Here, a difference is made between V-bending and U-bending.

- **V-bending**
  The bending punch and die are V-shaped. In the initial phase, air bending takes place, with the workpiece radius constantly changing. It is only when it reaches the last phase that the final form is imparted by bottoming the punch.

- **U-bending**
  In U-bending the workpiece is also given its final shape by bottoming the punch. In this case, to prevent the bottom from bulging out during bending, a backing pad is often used. During the bending process it already starts pressing against the bottom of the workpiece.

![Figure 5. Bending at right angles to the direction of rolling.](image-url)
Roll bending
During roll bending, the bending moment is created by three rolls. The top roll can be moved around the angle and the height of both lower rolls can be adjusted. Both are driven by a motor. By adjusting the relative positions of the rolls, any diameters can be produced, with the smallest diameter limited by the size of the bending rolls and the largest diameter limited by the plasticity criterion. 10
4.3. The hydraulic press brake

For this study, a Hydraulic Press Brake from the brand Maquinaria Laminova S.L. is used. In the next table is possible to see the features of the different kind of presses. The model G-4300 has been selected due to the characteristic of the process.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX POWER</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>LEXIT</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>INSTANC REVERE &amp;</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>TOTAL HEIGHT</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>TOTTAL WIDTH</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>DISTANCE FROM THE</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>HEIGHT FROM THE</td>
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4.4. Calculation of the Bending Force and Cycle Time

In accordance with the features of both steels and the hydraulic press brake, the following calculations are carried out:

**Domex 900**
- Length, $b = 3000$ mm
- Thickness, $t = 6$ mm
- Ultimate Tensile Strength, $R_m = 1000$ Mpa
- Bending radius, $R_i > 3t = 18$ mm
- Die opening width, $W = 10t = 60$ mm

**Weldox 1100**
- Length, $b = 3000$ mm
- Thickness, $t = 4$ mm
- Ultimate Tensile Strength, $R_m = 1250$ Mpa
- Bending radius, $R_i > 3.5t = 14$ mm.
- Die opening width, $W = 10t = 40$ mm

Bending force:

$$P_{DOMEX} = \frac{1\times 3000 \times 6^2 \times 1000}{10000 \times 60} = 288 \text{ tonnes}$$

$$P_{WELDOX} = \frac{1\times 3000 \times 4^2 \times 1250}{10000 \times 40} = 240 \text{ tonnes}$$

Because Weldox is stronger than ordinary steel, more force per millimetre of plate should be required to bend the material, but thanks to Weldox is stronger, the plate doesn’t need to be as thick.

This means that in practice, the requisite bending force is often lower.

**Angle of bend: $\alpha$**

Angle: $120^\circ$

Spring back: $11^\circ-18^\circ \sim 15^\circ$

Angle of bend = Angle – Spring back = $105^\circ$
**Bending distance: d**

Domex: \[ tg \left( \frac{\alpha}{2} \right) = \frac{W}{2d} \Rightarrow d = \frac{60}{2tg52.5} = 23.02 \text{ mm} \]

Weldox: \[ tg \left( \frac{\alpha}{2} \right) = \frac{W}{2d} \Rightarrow d = \frac{40}{2tg52.5} = 15.34 \text{ mm} \]

**Bending time**

Bending speed: 8 mm/s

Bending time = distance/speed

Domex \[ t_{\text{DOMEX}} = \frac{23.02}{8} = 2.88 \text{ seconds} \]

Weldox \[ t_{\text{WELDOX}} = \frac{15.34}{8} = 1.92 \text{ seconds} \]

**Cycle time**

\[ T = \text{Initial positioning} + \text{Bends} \cdot (\text{Approach} + \text{Bend} + \text{Return}) + (\text{Bends} - 1) \cdot \text{Repositioning} + \text{Exit} \]

Initial positioning time = 7 seconds (experimental data)

Approach time = Adjustment over the stop/Approach speed = 100/100 = 1 second

Return time = Adjustment over the stop/Return speed = 100/70 = 1.43 seconds

Repositioning time = 1 second (estimated data)

Exit time = 7 seconds (experimental data)

\[ T_{\text{DOMEX}} = 7 + 5 \cdot (1 + 2.88 + 1.43) + 4 \cdot 1 + 7 = 44.55 \text{ seconds} \]

\[ T_{\text{WELDOX}} = 2 \cdot [7 + 3 \cdot (1 + 1.92 + 1.43) + 2 \cdot 1 + 7] = 58.1 \text{ seconds} \]

\[ T_{\text{WELDOX}} = 130\% \cdot T_{\text{DOMEX}} \]
4.5. Cost Calculation

As the goal of this Master’s thesis is make a comparison between both steels, the general cost of the plant as well as the operator cost are not taken into account. Because they are practically the same.

The parts are introduced into the press by an ABB robot, model IRB 6660. The costs of that robot and also of the hydraulic press brake are considered already amortized since both were used in several preceding projects.

As Bending force is very similar for both steel, no economical difference is considered in this section. The economical difference between the steels comes from the cycle time. Next the above-mentioned difference is calculated.

Datas:

Power of the engines: $25 + 1 = 26 \text{ CV}$, it is deemed that the machine works with all this power during its movements. In compensation the consumption while the press is waiting for parts is not taken into account.

Power of the robot in normal movements: $3'8 \text{ kW}$

kWh price: $0'0799$

Times:

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<td>Positioning</td>
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<td>WELDOX</td>
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Table 5. Robot and press times.

Calculation:

$$Power_{HPB} = 26CV \cdot 0'736 \cdot \frac{kW}{CV} = 19'14 kW$$

$$HPBCost = 19'14 kW \cdot 0'0799 \cdot \frac{€}{kWh} = 1'529 \frac{€}{h} = 4'25 \cdot 10^{-4} \frac{€}{s}$$
RobotCost \[= 3'8kW \cdot 0'0799 \cdot \frac{€}{kwh} = 0'304 \cdot \frac{€}{h} = 8'43 \cdot 10^{-5} \cdot \frac{€}{s}\]

DomexTotalCost \[= \left[ 8'43 \cdot 10^{-5} \cdot \frac{€}{s} \cdot 18 \cdot \frac{s}{part} \right] + \left[ 4'25 \cdot 10^{-4} \cdot \frac{€}{s} \cdot 26'55 \cdot \frac{s}{part} \right] = 0'0128 \cdot \frac{€}{part}\]

WeldoxTotalCost \[= \left[ 8'43 \cdot 10^{-5} \cdot \frac{€}{s} \cdot 32 \cdot \frac{s}{part} \right] + \left[ 4'25 \cdot 10^{-4} \cdot \frac{€}{s} \cdot 261 \cdot \frac{s}{part} \right] = 0'0138 \cdot \frac{€}{part}\]

Although Weldox needs more time, because one part consists of two sheets, the cost is practically the same. This is due to Weldox is thinner and easier to bend, that mean smaller bending radius and die opening width. And so then the only benefit of the Domex regarding Weldox is that less time is neccesary for the process.
5. Welding methods

5.1. Types of bonding

There are different processes for joining metal parts, these can be subdivided into different categories in accordance with their action principle. Their bond can be form-closed, frictional or positive-substance bond (Figure 1). Frequently, it is not possible to make a clear distinction between closing shape and frictional bond, as some processes render a clear distinction between operating principles impossible.

![Classification of welding by their action principle](image)

A positive substance bond is mostly inseparable, and the bond takes place only by using additional material or consumables. The most frequent types of joints in this category are adhesive, soldered and welded joints. When welding materials, one has to distinguish between fusion welding and pressure welding. 5, 6, 7

5.1.1. Pressure and fusion welding.

Pressure welding depends on the application of high pressures and/or high temperatures, resulting in a strong plastification and a local deformation of the pieces to be joined in the welding area so that a bond between both pieces is made. Unlike pressure welding, fusion welding leads to a welding of the pieces by applying heat at the point of connection which fuses the pieces together and even joins a material. After the hardening of the mixed components, a solid joint occurs. The energy required for the
welding process is of a different kind for both types of procedure. Proven energy sources here are gas, arc welding, light, electron or plasma beams.

Pressure welding.
Pressure welding can be divided in several groups, such as:

- **Resistance welding:** it’s framed in this kind of welding although it involves fusion at the join. The material to be joined is fixed between two electrodes and a high current is applied through them, a local melting and are produced at the seam.

![ Resistance welding system ](image)

- **Cold pressure welding:** if sufficient pressure is applied to the cleaned mating surfaces to cause substantial plastic deformation the surface layers of the material are disrupted, metallic bonds form across the interface and a cold pressure weld is formed.

- **Friction welding:** in friction welding a high temperature is developed at the joint by the relative motion of the contact surfaces. When the surfaces are
softened a forging pressure is applied and the relative motion is stopped. Material is extruded from the joint to form an upset.

- **Diffusion bonding**: in diffusion bonding the mating surfaces are cleaned and heated in an inert atmosphere. Pressure is applied to the joint and local plastic deformation is followed by diffusion during which the surface voids are gradually removed. The components to be joined need to be enclosed in a controlled atmosphere and the process of diffusion is time and temperature dependent.

- **Explosive welding**: in explosive welding the force required to deform the interface is generated by an explosive charge.

- **Magnetically impelled arc butt welding (MIAB)**: in MIAB welding a magnetic field generated by an electromagnet is used to move an arc across the joint surfaces prior to the application of pressure.

**Fusion welding.**
As pressure welding, this kind of welding can be divided in several groups, such as:

- **Manual metal arc welding (MMA)**: this process is also known as shielded metal arc welding (SMAW) in USA and is still referred to as Stick welding in the UK fabrication industry. This process uses an arc as the heat source but shielding is provided by gases generated by the decomposition of the electrode coating material and by the slag produced by the melting of mineral constituents of the coating. In addition to heating and melting the parent material the arc also melts the core of the electrode and thereby provides filler material for the joint. The electrode coating may also be used as a source of alloying elements and additional filler material. The flux and electrode chemistry may be formulated to deposit wear- and corrosion-resistant layers for surface protection.

- **Submerged arc welding (SAW)**: It’s a consumable electrode arc welding process in which the arc is shielded by a molten slag and the arc atmosphere is generated by decomposition of certain slag constituents. The filler material is a continuously fed wire and very high melting and deposition rates are achieved by using high currents with relatively small-diameter wires.

- **Tungsten inert gas (TIG)**: this process is also known as gas tungsten arc welding (GTAW) in USA, wolfram inert gas (WIG) in Germany, and is still
referred to by the original trade names Argonarc or Heliarc welding in some countries. In this case the heat generated by an arc which is maintained between the workpiece and a non-consumable tungsten electrode is used to fuse the joint area. The arc is sustained in an inert gas which serves to protect the weld pool and the electrode from atmospheric contamination.

![Figure 8. The TIG process.](image)

**Metal inert gas (MIG) or metal active gas (MAG) welding:** It’s also known as gas metal arc welding (GMAW) in USA. It uses the heat generated by an electric arc to fuse the joint area. The arc is formed between the tip of a consumable, continuously fed filler wire and the workpiece and the entire arc area is shielded by an inert gas.

**Plasma welding:** This process uses the heat generate by a constricted arc to fuse the joint area, the arc is formed between the tip of a non-consumable electrode and either the workpiece or the constricting nozzle. A wide range of shielding and cutting gases are used depending on the mode of operation and the application.
• **Electron beam welding:** a beam of electrons may be accelerated by a high voltage to provide a high-energy heat source for welding. The power density of electron beams is high (10^{10} to 10^{12} Wm^{-2}) and “keyhole” welding is the normal operating mode. The problem of power dissipation when the electrons collide with atmospheric gas molecules is usually overcome by carrying out the welding operation in a vacuum.

• **Laser welding:** the laser may be used as an alternative heat source for fusion welding. The focused power density of the laser can reach 10^{10} or 10^{12} Wm^{-2} and welding is often carried out using the “keyhole” technique.
5.2. TIG

As it was mentioned before, in TIG welding the heat generated by an arc which is maintained between the workpiece and a non-consumable tungsten electrode is used to fuse the joint area. The weld pool and the electrode are protected by an inert gas, usually argon, supplied through a gas cup at the end of the welding gun. The main characteristics of the method are the stable arc and the excellent control of the welding result. In TIG welding filler material can be used applying the wire by hand, even though the supply of filler wire can be automated.

Welding of stainless steel, welding of aluminium and magnesium alloys and welding of copper are the main application for TIG welding. It is also suitable for welding all weldable materials, apart from lead and zinc, with all types of joints and in all welding positions. However, TIG welding is best suited to thin materials, from about 0.5 mm up to about 3 mm thick. In terms of productivity, TIG welding cannot compete with methods such as short arc welding.

The main advantages of this method are:

- High quality welds can be made on almost any weldable metal or alloy.
- Filler metal can be added to the weld pool independently of the arc current.
- Very pretty welds.
- Low spatter.
- No slag.
- Easy clean up.

The main disadvantages of this method are:

- Produces the slowest metal deposition rate of all the processes.
- Low welding current and more welding time.
- Very skilled worker.
- Expensive.

The necessary equipment to carry the TIG welding out is a welding gun, high-frequency generator for ignition of the arc, a power source, shielding gas and control equipment.

The welding gun must be easy to handle and well insulated. These requirements are more important for manual welding than for mechanical welding. The more utilized guns are water-cooled (current about 400 A) and air-cooled (about 200 A).

The high-frequency generator originates the arc, it produces a spark which supplies the necessary initial conducting course through the air for the low-voltage welding current. Another method of striking the arc is the 'lift-arc' method, which requires the use of a controllable power source. The arc is struck by touching the electrode against the workpiece, but the special power source controls the current to a sufficiently low level to prevent any adverse effects.
The power source is normally of DC, with the negative pole connected to the electrode. Nonetheless when welding aluminium, the oxide cloak is snap only if the electrode is connected to the positive pole. So aluminium and magnesium are normally welded with AC. TIG power sources are generally electronically controlled.

The shielding gases are different for different materials. For unalloyed steels, low-alloyed steels and stainless steels, Argon is generally used. For mechanical welding of all these metals, the argon may be used with an admixture of hydrogen or helium. Other gases can be addition for special welds.

The necessary control equipment depends on which is the mechanized grade of the welding process. However, it is usual for the pre-flow and post-flow of the shielding gas, and the HF generator, to be automatically controlled. Crater filling by slope-down of the current, and the ability to pulse the current, are also often employed. Gas pre-flow and post-flow protect the electrode and the weld pool against oxidation.

The electrode material should have low electrical resistance, high melting point, good emission of electrons and good thermal conductivity. The material that best meets these requirements is tungsten. Pure tungsten electrodes are used when welding light metals with AC: for other welding applications, the electrodes often incorporate an admixture of 2 % thorium oxide, which improves the stability of the arc and makes it easier to strike. As thorium is radioactive, but is not so dangerous, alternative non-radioactive oxide additives that can be used are those of zirconium, cerium or lanthanum.

An important variable is the electrode diameter. The best arc stability is obtained with a high current load, which means that the diameter should be chosen so that the electrode tip is neither too hot nor too cold. For DC welding, the tip of the electrode is ground to an approximate 45° angle. The use of a special electrode grinding machine guarantees this angle is always the same, as this would otherwise affect the arc and its penetration into the workpiece material. Electrodes intended for use with AC welding are not ground: instead, the current is increased until it melts the tip of the electrode into a soft, rounded shape.

Fillers for TIG welding are used in the form of a wire, which is fed into the joint either by hand or mechanically. Welding performance can be improved by using the hot wire system, to feed the wire at an elevated temperature. Thin materials (up to 3-4 mm) can be butt-welded from one side, with the weld metal consisting entirely of molten workpiece material. Higher workpiece thicknesses require some form of joint preparation, with a filler being added in order to fill the joint. The use of fillers is always recommended when welding mild steel in order to reduce the risk of pores. 5, 6, 7

5.2.1. Welding of Domex 900.

Due to its low content of alloying elements, Domex is not susceptible to hot or cold cracking due to hydrogen embrittlement and therefore no preheating of the workpiece is
necessary. All common fusion welding methods can be employed for welding Domex advanced high strength steels. The member under improvement was welded by TIG method.

In order to reach the required tensile strength of the welded joint, both the weld metal and the HAZ (heat affected zone) must have sufficient strength. Several factors affect the strength of the welded joint e.g. filler metal used, chemical composition, heat input, interpass temperature, etc. The strength of the weld metal (N/mm²) is mainly determined by the filler metal.

The heat input in fusion welding is the amount of heat supplied to the material during welding. The following formula is generally used for calculating the heat input:

\[ E = \frac{U \cdot I \cdot 60}{v \cdot 1000} \text{kJ} \]

Where: \( U = \) voltage
\( I = \) current
\( v = \) welding speed

\[ Q = \eta \cdot E \]

Where \( \eta = \) arc efficiency (\( \eta = 0.6 \) in TIG)

Multi-pass welding may cause the temperature in the welded joint to rise to a level that is harmful to the material, which will cause the strength to drop. This is most critical for short welds, i.e. below 500 mm, since the temperature of the material will not have time to drop before the next bead is welded. In order to limit the temperature rise so that it will not be harmful to the material, a maximum inter-pass temperature may be employed. This means that the temperature at the starting point for the next weld bead must not exceed a specified value. This it is not a problem in the case of this report, due to the length here is 3000 mm.

The choice of the filler metal has been carried out with the advise of the SSAB’s Knowledge Service Center. Their recommendation is to use AWS A5.28 ER100S-X. These filler metals are however undermatching in relation to the strength of the Domex 900 material. But there are not any filler metals for TIG-welding with higher strength than the above mentioned. It should apply a lower heat input because it increases the strength as well as the impact toughness of the welded joint.
5.2.2 Cost calculation

In this section, only the mainly welding costs are considerate.

Datas:

Operator factor, $\text{OF} = 0.75$ (this factor has been improved with an assistant)

Welder cost, $\text{WC} = 20 \, \text{€/h}$

Assistant cost, $\text{AC} = 12\, \text{€/h}$ (he prepares the parts while the welder is welding)

Velocity of welding, $\text{VW} = 0.06 \, \text{m/min}$

Cross-sectional area, $A = 0.156 \, \text{cm}^2 + 10\% = 0.1716 \, \text{cm}^2$

Velocity of deposition, $\text{VD} = 2 \, \text{kg/h}$

Deposition efficiency, $\text{DE} = 0.95$

Filler metal price, $\text{FP} = 10 \, \text{€/kg}$

Shielding gas price, $\text{GP} = 8.05 \, \text{€/m}^3$

Shielding gas flow rate, $\text{GF} = 0.36 \, \text{m}^3/h$

Power of the TIG equipment, $\text{P} = 2 \, \text{kW}$

kWh price, $\text{PK} = 0.0799 \, \text{€/kWh}$

Calculation:

Deposition rate, $\text{DR} = A \cdot \rho_{\text{steel}} = 0.1716 \cdot 10^{-4} \text{m}^2 \cdot 7800 \, \text{kg/m}^3 = 0.1338 \, \text{kg/m}$

Time per part, $T = \frac{\text{DR}}{\text{VD}} \cdot L = \frac{0.1338 \, \text{kg/m} \cdot 3600 \, \text{s/h}}{2 \, \text{kg/h}} \cdot 3 \, \text{m} = 722.52 \, \text{s}$

Labor cost, $\text{LC} = \frac{(\text{WC} + \text{AC}) \cdot \text{DR}}{\text{VD} \cdot \text{OF}} = 2.85 \, \text{€/m}$

Filler metal consumption, $\text{Fc} = \frac{\text{DR}}{\text{DE}} = 0.1409 \, \text{kg/m}$
Filler metal cost, \[ FC = FP \cdot FC = 1.41\text{€}/m \]

Shielding gas cost, \[ GC = \frac{GP \cdot GP}{60 \cdot VW} = 0.805\text{€}/m \]

Power cost, \[ PC = \frac{DR}{VD \cdot OF} \cdot P \cdot PK = 0.014\text{€}/m \]

\[ WeldingCost = LC + FC + GC + PC = 5.08\text{€}/m \]

**Total Welding cost = 15.24 €/part**
5.3. Laser welding

The implement of the Laser welding in the industry had a strong increase in the last years. The possibilities of the Laser light, like the several and unique properties of the Laser, it is parallel and highly concentrated, also it can therefore be conducted, by mirrors or glass fibers, to a welding position that is remote from the power unit, or the fact that it is also monochromatic, i.e. at a single definite wavelength, which depends on the type of laser used, makes the laser really competitive in the industrial market.

Description

Now days, difference companies are improving in the way of the creation of the laser beam, but we will do a rough description of the process of the Laser welding.

The laser beam is focused by a lens or mirrors into a point only a few tenths of a mm in diameter in order to provide a high energy density. The focus point is arranged to fall on, or slightly below, depending of the type of the surface of the workpiece. When the laser reach the laser point, the material immediately melts, with some even being vaporized, and this vaporized creates a molten pool and a keyhole. The vaporized metal in the keyhole forms a plasma, or like we called before a molten pool, which, being a good absorber of the incident light, further improves energy absorption and so efficiency of the process. See Figure 10. Shielding gas is used, to prevent air from reacting with the material and to protect the lens from spatter and vapor, but we must bear in mind, that the gas shroud can affect the formation of plasma which may block or distort the beam and thus the absorption of the beam into the work piece.

One of the big advantages of the laser is that, as soon as the beam has moved on, and the heat input has been interrupted, the metal solidifies fast, as the heated zone is small. As a result, the size of the heat-affected zone is also small, this is a huge advanced because a small heat-affected means less distortions and less defects in the welding. The penetration of the weld depends on the laser output power. Another condition that we should attend is the wavelength of the laser, and the reflectivity of the surface, due to the high absorptivity within the keyhole, and this carry out big difference when welding with long or short wavelengths. No filler materials are used, except for hybrid welding.

Two of the main application areas for laser welding are the automotive industry and shipyards. In the automotive industry is really useful for the welds with relative thin sheet. In the shipyard is needed more powerful lasers to increase the penetration. For this area is made big advanced and research because of the special characteristic of the laser for this process.
For be achieved in the laser deep, narrow penetration it is reached by keyhole welding methods, so it is ensured a complete penetration. The welding speed depends on two parameters, the laser power of the machine, and the thickness of the materials that are being welded, with less thickness, higher speed: up to 10-50 m/min, and even 100 m/min when welding foils. If we compare the speed of difference types of welding, we can said that laser welding is, in other words, fast: about twice as fast as plasma welding and eight times faster than TIG welding. Pore-free high-strength welds, excellent dimensional tolerances and high productivity make the method superior to most others in many applications. In addition, laser welding is clean and quiet.

One of the big drawbacks of laser welding is that the low width/depth ratio of the weld geometry can result in thermal cracking. In addition, hardening steels can be locally hardened by the rapid rate of cooling. As the laser beam is only a few tenths of a millimetre in diameter, it means that the method is tolerance-sensitive, and therefore requires highly accurate jigs and fixtures. However, thinner materials can often be overlap-welded, which reduces the accuracy requirements. Investment costs are high, but prices are coming down and laser welding can be expected to be much more widely used in the future.

Laser welding is often used for welding materials that can accept only a low heat input, e.g. certain stainless steels and hardened materials, or for welding components in the electronics industry. The method also used where complicated parts require high precision, e.g. in the automotive, general engineering and aerospace industries.
Equipment
In the market, we can purchase several different kinds of laser for different characteristics, but the commonest types of welding lasers are the C0₂ laser and the Nd:YAG laser, attending to the different requirements needed for each kind of process. For example, the latter tending to be used for thinner materials and the former for thicker. Another property that we should bear in mind is the type of laser beam, may be either pulsed or continuous.

The C0₂ laser
C0₂ lasers available today have much higher powers than Nd:YAG lasers. This characteristic is an advantage for some process like welding and cutting applications because the welding speed is proportional to output power, this means that the C0₂ lasers can weld more quickly. Alternatively, the higher power means that C0₂ lasers can weld plate up to 26 mm thick. However, the C0₂ laser have some drawbacks in compare with the Nd:YAG. One problem is that a considerable portion of the beam energy is reflected by certain materials: different wavelengths are absorbed to different extents, which means that the light from C0₂ lasers are reflected more readily than that from YAG lasers. This is particularly noticeable when welding materials such as aluminium or magnesium alloys.

Another disadvantage is the dimensions of the C0₂ laser, because for generates the laser, we need to produce light in a tube through which a mixture of gases (including C0₂) flows, the energy input is by means of an electric discharge through the gas. The light is usually conveyed to the welding head and focused by mirrors. A shielding gas (often helium or an argonhelium mixture) is used to protect the lens and the weld: it helps to limit the amount of energy-absorbing plasma formed above the surface of the joint. In this respect, helium is to be preferred, due to its high ionisation energy and for the transmit it. So, we need a complex machine to produce a wavelength of 10.6 pm, and obtain the laser beam. Finally, Gold, silver and copper are also difficult to weld with C0₂ lasers.

The Nd:YAG laser
In this type of laser, the active substance is neodymium, in the form of a dopant in a transparent rod of yttrium aluminium garnet. For the supply of the energy, we use a flash tube, of the same principal as used in cameras. The light output wavelength is 1.06 pm, i.e. considerably shorter than that of the C0₂ laser, but still within the invisible infra-red section of the spectrum. An important difference is that the shorter wavelength enables the light to be carried by fibre optics and focused with ordinary lenses. This gives substantial practical benefits and makes it possible to use the laser for robot welding. The shielding gas, that normally is used, argon or argon/C0₂ gas, carry out less problems due to the presence of absorbing plasma in welding process. Also, we can weld without shielding gas, in welding spot welds or at low powers, with acceptable results.
This laser is particularly suitable for welding otherwise difficult materials such as tantalum, titanium, zirconium, Inconel etc. But the laser have more problems for cutting, because the big drawback is that it is not available with such high power outputs as is the CO₂ laser, and so tends to be limited to metal thicknesses up to 6 mm, and the power is not enough for the process of cutting steel. However, development is increasing the outputs available: in combination with the ability to use fibre optic light conductors, this makes this type of laser potentially very attractive.

**Diode lasers**

For process that needs high-power lasers, normally is used diode laser, because the other types of high power lasers are bulky, very expensive and often have very poor efficiency. The diode laser are, in principle, the same as those fitted in every CD player. If we join a large number of them, it is possible to produce sufficient laser light power to weld thin metal. However, they are still expensive, with poor beam quality, i.e. it is difficult to concentrate the beam sufficiently.

**Protection**

For the safety of the operator, different type of material is needed depending of the laser. A pair of ordinary glasses is sufficient to absorb the radiation from a CO₂ laser and to protect the cornea from being damaged by the beam. However, the light from a Nd:YAG laser requires special protective goggles, as even the reflected light from the workpiece can damage both the cornea and the retina, as well as cause cataracts in the eye's vitreous body. The reason is that the lens of the eye focuses the light on the retina. Even with protective goggles, it is therefore dangerous to look hard (i.e. other than fleetingly) at anything in the vicinity of a Nd:YAG laser beam while welding is in progress.

**Cladding**

For the requirements of industry now a days, we need metal with special qualities, that we cannot find in the nature, so many process are develop for achieve this requirements. The wear resistance and corrosion resistance of surfaces can be improved by applying a suitable cladding layer to them, either in small local areas or over the entire part. If an appropriate surface cladding is required for new manufacture or for repairs, this method can be used wherever. With the cladding, we produce a thin layer of pore-free weld metal, with a good surface finish and little mixing with the substrate material.

For this process, we require less energy than for other cladding methods, which means that there is less thermal distortion and a more finely grained structure. A flux bed is normally used like cladding material, but also, it can theoretically be applied in the form of wire, foil, chips etc. Welding is carried out under a shielding gas to prevent the formation of oxides. 5, 7, 9, 11
5.3.1. Hybrid welding

Laser welding has important drawbacks specially related to ability to bridge a gap. These limitations can be solved by hybrid welding. Hybrid welding refers to a combination of two welding methods, laser welding and an arc welding method such as MIG or plasma welding. MIG/MAG has become the most suitable arc types to combine with the laser source in a hybrid welding tool, because of its ability to offer easy addition of filler material. Combining a laser with MIG/MAG welding, which wire provides molten material that fills the joint and thus reduces the requirements for exact positioning of the two parts that would otherwise be required for laser welding alone. In addition, when welding fillet joints, this combination provides reinforcement of the joint. This also reduces the risk of undercutting, which can easily occur with laser welding, and which unfortunately seriously reduces fatigue strength. However, in comparison with ordinary MIG/MAG welding, the welding speed is considerably higher, due to use of the laser.

In the process, heat, momentum and molten filler material are transferred to the welding zone by the MIG/MAG process in order to enhance the action of the deep penetration welding laser beam. The penetration is determined by the laser alone, and the arc maintains the welding speed, even in the case of large gap. 5,9,11
This process has several advantages but also disadvantages:

**Advantages**
- High ability to bridge a gap.
- Increase speed welding in presence of gaps as compared with laser welding.
- Increase of weld penetration.
- Pore reduction.
- The use of the hybrid welding process seems to be a useful way to improve the ductility as compared to entirely laser welded parts.
- Welding of highly reflective materials is easier than in laser welding.
- Reduced equipment cost as a lower power laser can be used.
- Higher electrical efficiency.

**Disadvantages**
The main drawback of hybrid-laser welding is the fact that hybrid-laser welding involves a large number of parameters. It is not only an addition of the number of parameters for the laser welding process and a conventional process, new and equally important parameters are added:
- Type of arc welding.
- Relative position between laser and arc torch.
- Ratio between laser and arc source.
- Angles of arc torch and laser beam.

### 5.3.2 Cost calculation

For Hybrid welding it is necessary a new completely installation. This installation consists of the laser generator, laser head, turn table and a specific laser welding robot (with specific software). The laser is IPG and its power 3 kW. The cost of the complete installation is 650,000 €.

The estimated production is around 100,000 cranes, this means 500,000 parts due to each crane has five members.

In hybrid welding to increase assurance against cold cracking, sometimes it is necessary to preheat the material. But Weldox 1100 must not be subjected to preheating neither post-heating treatment. This is because Weldox has lower content of alloy elements.

**Data:**

Operator factor, \( OF = 0.95 \) (this includes total automation, tooling in peak condition, flat position of welding, etc.)
Operator cost, \( OC = 12 \, \text{€/h} \)

Velocity of welding, \( VW = 0.48 \, \text{m/min} \) (it is required a lower welding speed to achieve full penetration)

Cross-sectional area, \( A = 0.1344 \, \text{cm}^2 + 10\% = 0.1478 \, \text{cm}^2 \)

Velocity of deposition, \( VD = 10.5 \, \text{kg/h} \)

Deposition efficiency, \( DE = 0.90 \)

Filler metal price, \( FP = 10 \, \text{€/kg} \)

Shielding gas price, \( GP = 8.05 \, \text{€/m}^3 \)

Shielding gas flow rate, \( GF = 0.9 \, \text{m}^3/\text{h} \)

Power of the laser equipment, \( P_1 = 4 \, \text{kW} \)

Power of the MIG equipment, \( P_M = 2 \, \text{kW} \)

kWh price, \( PK = 0.0799 \, \text{€/kWh} \)

**Calculation:**

Deposition rate, \( DR = A \cdot \rho_{\text{STEEL}} = 0.1478 \cdot 10^{-4} \, \text{m}^3 \cdot 7800 \, \text{kg/m}^3 = 0.1153 \, \text{kg/m} \)

Time, \( T = \frac{DR}{VD} = \frac{0.1153 \, \text{kg/m} \cdot 3600 \, \text{s/h}}{10.5 \, \text{kg/h}} = 39.53 \, \text{s/m} \)

Labor cost, \( LC = OC \cdot T = 12 \, \text{€/h} \cdot \frac{39.53 \, \text{s/m}}{3600 \, \text{s/h}} = 0.13 \, \text{€/m} \)

Filler metal consumption, \( Fc = \frac{DR}{DE} = 0.1281 \, \text{kg/m} \)

Filler metal cost, \( FC = FP \cdot Fc = 1.281 \, \text{€/m} \)

Shielding gas cost, \( GC = \frac{GF \cdot GP}{60 \cdot VW} = 0.252 \, \text{€/m} \)
Power cost, \[ PC = \frac{DR}{VD \cdot OF} \cdot (P_i + P_m) \cdot PK = 0.0055€/m \]

Welding Cost = LC + FC + GC + PC = 1.67€/m

Total Welding cost = WC \cdot 2 \text{w} \cdot 3 \text{m} = 10.01€/part
But this cost has to be increased with the cost of the installation.

Cost of the installation, CI = \[ \frac{650000€}{500000 \text{parts}} = 1.3€/\text{part} \]

This results in a total hybrid welding cost per part of 11.31€.
6. Conclusions

6.1. Benefits by change material

Domex: hot-rolled steel sheet (low alloy, cold forming)

Weldox: high strength structural steel plate (high purity, excellent machining properties)

The main profits due to change material from Domex 900 to Weldox 1100 are:

1. Reduce the thickness from 6 mm to 4 mm.
2. Weldox is lighter and stronger → reduce crane weight, or increase lifting capacity without changing crane weight.
3. Higher price but less material used → material cost decrease.
4. Welding → reduces the amount of consumables and the welding hours → save more cost.
5. Less ballast to be used → reduces vessel draught and fuel consumption.

And due to the change of the welding method, from TIG to Laser+MIG:

1. The combination of the laser process and the arc process results in an increase in both weld penetration depth and welding speed.
2. Less distortion and high thickness.
3. Lower width.
4. Reduces cycle and “reworks” time (final machining).
6.2. Manufacturing cost. Economical saving

The following table shows the manufacturing costs per part in both processes:

<table>
<thead>
<tr>
<th></th>
<th>Domex 900</th>
<th>Weldox 1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>353’60 €</td>
<td>284’28 €</td>
</tr>
<tr>
<td>Cutting</td>
<td>2’45 €</td>
<td>2’83 €</td>
</tr>
<tr>
<td>Bending</td>
<td>0’013 €</td>
<td>0’014 €</td>
</tr>
<tr>
<td>Welding</td>
<td>15’24 €</td>
<td>11’31 €</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>371’30 €</strong></td>
<td><strong>298’43 €</strong></td>
</tr>
</tbody>
</table>

Table 6. Manufacturing costs.

The study carried out proves that a saving of 72’87 € per part can be achieved. This saving is achieved basically in the reduction of the price of the raw material. Also an important saving is obtained in the welding, due to less time is necessary to weld.
6.3. Environmental load

Initially, as executed calculation show in Table 7 and 8, obtaining of the new steel (Weldox 1100) is more harmful with environment than the old one (Domex 900), it is due to new steel contains Molybdenum what presents a high environmental load because it is a limited resource.

<table>
<thead>
<tr>
<th>Material</th>
<th>Raw material Index (ELU/Kg)</th>
<th>X_i</th>
<th>M_i(Kg)</th>
<th>Environmental Load (ELU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0’09</td>
<td>0’97205</td>
<td>137’2927114</td>
<td>12’35634402</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>0’0015</td>
<td>0’21186057</td>
<td>0</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0’005</td>
<td>0’7062019</td>
<td>0</td>
</tr>
<tr>
<td>Mn</td>
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<td>0’021</td>
<td>2’96604798</td>
<td>2’877066541</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>0’0002</td>
<td>0’028248076</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>-</td>
<td>0’0001</td>
<td>0’014124038</td>
<td>0</td>
</tr>
<tr>
<td>Al</td>
<td>2’9</td>
<td>0’0015</td>
<td>0’021186057</td>
<td>0’061439565</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total 15’29485013</td>
</tr>
</tbody>
</table>

Table 7. Domex 900 Environmental Load

<table>
<thead>
<tr>
<th>Material</th>
<th>Raw material Index (ELU/Kg)</th>
<th>X_i</th>
<th>M_i(Kg)</th>
<th>Environmental Load (ELU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0’09</td>
<td>0’9309</td>
<td>89’2063411</td>
<td>8’028570695</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>0’0021</td>
<td>0’20123893</td>
<td>0</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0’005</td>
<td>0’4791403</td>
<td>0</td>
</tr>
<tr>
<td>Mn</td>
<td>0’97</td>
<td>0’014</td>
<td>1’34159284</td>
<td>1’301345055</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>0’0002</td>
<td>0’01916561</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>-</td>
<td>0’0005</td>
<td>0’0047914</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
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<td>0’0005</td>
<td>0’0047914</td>
<td>0’013895069</td>
</tr>
<tr>
<td>Nb</td>
<td>-</td>
<td>0’0004</td>
<td>0’03833122</td>
<td>0</td>
</tr>
<tr>
<td>Cr</td>
<td>8’8</td>
<td>0’008</td>
<td>0’76662448</td>
<td>6’74295424</td>
</tr>
<tr>
<td>V</td>
<td>-</td>
<td>0’0008</td>
<td>0’07666245</td>
<td>0</td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>0’001</td>
<td>0’09582806</td>
<td>0</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
<td>0’0002</td>
<td>0’01916561</td>
<td>0</td>
</tr>
<tr>
<td>Al</td>
<td>-</td>
<td>0’0002</td>
<td>0’01916561</td>
<td>0</td>
</tr>
<tr>
<td>Mo</td>
<td>1500</td>
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<td>0’67079642</td>
<td>1006’19463</td>
</tr>
<tr>
<td>Ni</td>
<td>24’3</td>
<td>0’03</td>
<td>2’8748418</td>
<td>69’85865574</td>
</tr>
<tr>
<td>N</td>
<td>-</td>
<td>0’0001</td>
<td>0’00958281</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total 1092’143392</td>
</tr>
</tbody>
</table>

Table 8. Weldox 1100 Environmental Load

However, it seems to be that resulted benefits from the weight saving will compensate this extra initial damage, since during its useful life the new component will provide us with a saving in the form of potential energy that principally will be reflected into two aspects, the first one will be a saving in the engine consumption, and the second one, derived from the first one, consist of a lower concentration of pollutant gases emitted by engine.
The potential energy saving will be:

$$\Delta Ep = \frac{m_{\text{WELDOX}} \cdot g \cdot h_2}{m_{\text{DOMEX}} \cdot g \cdot h_1}$$

The objective is to know the benefit obtained lifting the load to the same height. So $h_1=h_2$. The potential energy difference depends on the weight of the crane member.

$$\Delta Ep = \frac{m_{\text{WELDOX}}}{m_{\text{DOMEX}}}$$

The benefit will be:

$$\Delta Ep(\%) = (1 - \frac{m_{\text{WELDOX}}}{m_{\text{DOMEX}}}) \cdot 100 = 33\%$$
6.4. Discussions and further work

Lighten the boom, therefore, will contribute substantial benefits for final customer at time of working with the crane:

- Both vertical movements and horizontal ones of the useful load will need a lower supply of energy.
- Decrease crane ensemble mass, will involve a lower consumption on displacement to the work points.
- Increase in load what crane is able to raise at the same height.

Further work could be to study if the higher slenderness of the new boom will produce a series of problems due to the greater vibrations that will occur now. Also to verify deeper that the executed changes to the crane boom contribute to get a better operation of the machine (multibody dynamic simulation), and produce less harmful effects on environmental, since raw materials obtaining to the final disposal of the part.
7. References


[2] SSAB technical brochures


[5] John Norrish; *Advance Welding Processes*


[15] Websites:
  - www.ssab.com
  - www.staplaurultrasonics.com
  - www.lincolnelectric.com
  - www.laminova.net
8. Attachments

1. Data sheet of Domex 900
2. Data sheet of Weldox 1100
Domex 900
Hot rolled ultra high strength structural steel

Product
Domex 900 is a thermomechanical rolled ultra high strength steel with minimum yield strength of 900 MPa.

Applications
Domex 900 is developed with weight sensitive load carrying structures in mind. The material shows its true value in applications where the strength of the material can be used to increase the payload, or reduce the weight of the application itself, for instance cranes, lifting devices, chassis and equipment for heavy vehicles and other structures having very high demands on low weight.

Mechanical properties

<table>
<thead>
<tr>
<th>Yield Strength $R_p$, MPa (N/mm²)</th>
<th>Ultimate Tensile Strength $R_m$, MPa (N/mm²)</th>
<th>Elongation $A$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>1000</td>
<td>8</td>
</tr>
</tbody>
</table>

(The mechanical properties are tested along the rolling direction.)

Testing
The testing of the material conforms to EN 10049.

Delivery conditions
Domex 900 is delivered as thermomechanical rolled.

Dimensions

<table>
<thead>
<tr>
<th>Thickness mm</th>
<th>Width mm</th>
<th>Length mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 - 6.00</td>
<td>900 - 1100</td>
<td>1000 - 13000</td>
</tr>
</tbody>
</table>

Impact toughness
The impact toughness is tested as Charpy V-notch test, with both longitudinal and transverse test pieces. The test is carried out in accordance with EN 10045-1, for thicknesses from 6 mm and upward.

<table>
<thead>
<tr>
<th>Thickness mm</th>
<th>Test temperature Degree Celsius</th>
<th>Impact energy min Joules/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>t &lt; 6</td>
<td>t &gt; 6</td>
<td>-60°C</td>
</tr>
</tbody>
</table>

Note: 33.75 Joules/cm² corresponds to 27 Joules for a half size Charpy V-notch test specimen.

Bending
Minimum permissible inner bending radius is 3.0 x thickness for a 90° bend, for both longitudinal and transverse bending direction. When bending Domex 900 it is important to have a punch radius equal to, or larger than, minimum permissible bending radius.

Heat treatment and fabrication
Domex 900 has obtained its mechanical properties by temperature controlled rolling and is not suited for applications requiring hot working or heat treatments at temperatures above 200°C since the material then may lose its guaranteed properties.

Tolerances
The tolerances conform to EN 10051. More narrow tolerances are available on request.

Surface condition
Domex 900 is supplied in as rolled (black) or in pickled condition.
Chemical composition

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>CEV</th>
<th>CET</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.1</td>
<td>0.14</td>
<td>2.1</td>
<td>0.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>max</td>
<td>0.1</td>
<td>0.34</td>
<td>2.1</td>
<td>0.03</td>
<td>0.08</td>
<td>0.06</td>
<td>0.07</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The metglas is refined.
In addition, Ni(Ni,Fe)Cr may be added.

CEV = C + \frac{Mn + S}{3} + \frac{Si + P + 0.5Cr}{3}

CET = C + \frac{Mn + S}{2} + \frac{Si + P + 0.5Cr}{2}

Welding

The low contents of carbon, phosphorus and sulphur enable all conventional welding methods to be readily used for Domes 900.

Domes 900 has low carbon equivalent relative its strength.

As a result of the lean chemistry, no preheating is necessary when welding at room temperature.

To reduce the risk of hydrogen cracking, filler materials which give a hydrogen content of maximum 5 ml/100 gram in the weld metal are recommended.

Examples of recommended filler materials are

<table>
<thead>
<tr>
<th>MMA Manual metal arc</th>
<th>SAW Submerged arc welding</th>
<th>RSW/MAW Gas metal arc</th>
<th>FCAW Flux cored arc welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANG 105.5</td>
<td>ANG 105.2</td>
<td>ANG 55.26</td>
<td>ANG 55.26</td>
</tr>
</tbody>
</table>

Note: 105-1050 to 1051 and 205-2050 to 2051.

For more detailed information regarding welding, please contact our Knowledge Service Centre.

Knowledge Service Center will be pleased to assist with additional information regarding Domes 900 and other products from SSAB Swedish Steel.

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Germán Rúa Collazo
Manufacturing sustainability and reengineering analysis of a crane boom member
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HIGH STRENGTH STRUCTURAL STEEL PLATE

WELDOX 1100 is a general structural steel with a minimum yield strength of 1100 MPa.

Applications
Load carrying structures having very high demands on low weight.

Designation
WELDOX 1100E with guaranteed impact toughness at -40°C.
WELDOX 1100F with guaranteed impact toughness at -60°C.

Chemical composition
(Analytical analysis)

<table>
<thead>
<tr>
<th>Element</th>
<th>C*</th>
<th>Si*</th>
<th>Mn*</th>
<th>P</th>
<th>S</th>
<th>Nb*</th>
<th>Cr*</th>
<th>Ni*</th>
<th>Cu</th>
<th>Ti</th>
<th>Al*</th>
<th>Mo*</th>
<th>Ni**</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>max %</td>
<td></td>
<td></td>
<td></td>
<td>max</td>
<td>max</td>
<td>max</td>
<td>max</td>
<td>max</td>
<td>max</td>
<td>max</td>
<td>max</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.21</td>
<td>0.50</td>
<td>1.40</td>
<td>0.020</td>
<td>0.005</td>
<td>0.005</td>
<td>0.04</td>
<td>0.00</td>
<td>0.08</td>
<td>0.10</td>
<td>0.02</td>
<td>0.020</td>
<td>0.70</td>
<td>3.0</td>
<td>0.010</td>
</tr>
</tbody>
</table>

*Intentional alloying elements: The steel is grain-refined

Plate thickness

<table>
<thead>
<tr>
<th>CEV</th>
<th>CET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical values</td>
<td>%</td>
</tr>
<tr>
<td>0.59</td>
<td>0.41</td>
</tr>
</tbody>
</table>

WELDOX 1100E
- 8 mm: 0.59
- 20 mm: 0.41

WELDOX 1100F
- 8 mm: 0.60
- 20 mm: 0.60

Mechanical properties

<table>
<thead>
<tr>
<th>Plate thickness (mm)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 - 4.9</td>
<td>1100</td>
<td>1250 - 1550</td>
<td>3</td>
</tr>
<tr>
<td>5.0 - 25.0</td>
<td>1100</td>
<td>1250 - 1550</td>
<td>10</td>
</tr>
</tbody>
</table>

* For transverse test pieces

1 MPa = 1 N/mm²
WELDOX 1100
Data sheet

<table>
<thead>
<tr>
<th>Impact properties</th>
<th>Steel grade and quality</th>
<th>Test temperature °C</th>
<th>Impact energy 2) for test on transverse Charpy V Impact test specimen 2) min. J</th>
</tr>
</thead>
<tbody>
<tr>
<td>WELDOX 1100E</td>
<td>–40</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>WELDOX 1100F</td>
<td>–60</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

2) Unless otherwise agreed, transverse impact testing according to EN 10025 option 30 will apply.
3) For plate thicknesses less than 12 mm, subsize Charpy V specimens are used. The specified minimum value is then proportional to the cross-section of the specimen.

Testing

Testing according to EN 10025.

Delivery condition

Q Quenched or quenched and tempered at our discretion.

Dimensions

WELDOX 1100 is supplied in plate thicknesses of 6-25 mm.

More detailed information on dimensions is provided in our brochure 42-General Product Information WELDOX, HARBUX and ARMOX-UK.

Tolerances

- All plates are produced with AccuRollTech™ thickness precision guarantee.
- AccuRollTech™ meets the requirements of EN 10 120, but offers more narrow tolerances.
- Tolerances on flatness according to Class N (Normal tolerances) according to our brochure.

More detailed information is given in our brochure 42-General Product Information WELDOX, HARBUX and ARMOX-UK as well as at www.weldox.com

Surface condition

According to EN 10163-2, Class A, Subclass 1 (repair by welding is allowed).

General technical delivery requirements

According to our brochure 42-General Product Information WELDOX, HARBUX and ARMOX-UK.

Heat treatment and fabrication

WELDOX 1100 has obtained its mechanical properties by a quenching process.

WELDOX 1100 is not suited for applications requiring hot working at temperatures above 200°C since the material may then lose its guaranteed properties.

For information concerning welding and fabrication, see our brochures on www.weldox.com or consult our Technical Customer Service.

Appropriate health and safety precautions must be taken when welding, cutting, grinding or otherwise working on the product. Grinding, especially of primer coated plates, may produce dust with high particle concentration.