Influence of Defects and Geometry in Welded Joints

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Influence of Defects and Geometry in Welded Joints

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Influence of defects and geometry in welded joints

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ABSTRACT

In most types of industrially manufactured products there are usually one or more joints present. These joints could be made using many procedures including welding. Independent of joining procedure however, the homogeneity and mechanical strength of the joints in a product tend to control the lifetime and overall performance of the product itself.

Even if the general level of mechanical strength in a certain type of joint is good the presence of different types of inhomogeneities ("defects") will often decrease both the static and the dynamic strength. The geometry of the joint also plays an important role here.

In this thesis, different mechanisms for formation of defects in a welded joint are described for the three welding processes, Metal Inert Gas/Metal Active Gas (MIG/MAG), laser and Friction Stir Welding (FSW).

The influence of the geometry of a welded joint on its mechanical strength (both static and dynamic) is also discussed for one the welding processes, FSW.

The results in thesis shows, for each welding process, that weld defects could be avoided if the combination of parent material and process conditions is chosen in a favourable way.

It is also shown that a good weld quality can be combined with a high productivity. It must also be stated that the mechanisms for formation of a certain kind of weld defect, e.g. lack of fusion, could be different for each welding process.

Keywords: MIG/MAG, FSW, Laser, Defects, Lack of fusion, fatigue strength, geometry
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LICENTIATE THESIS

This thesis consists of a literature review and the following papers

Paper 1

Nerman, P.
Aspects on problems with lack of fusion in MIG/MAG-welding, IIW-XI-767-02, presented at the annual IIW-assembly, commission XI (pressure vessels), in Copenhagen 2002

Paper 2

Nerman, P. and Andersson, J.
Formability of laser welded high strength dual phase (DP) sheet steels
To be published

Paper 3

Nerman, P.
Friction Stir Welding of lap joints in aluminium alloys
To be published

Paper 4

Nerman, P.
Fatigue Strength of Mixed Al-joints performed with FSW, presented at the 4th international FSW-conference in Utah, USA, 2003
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1. INTRODUCTION

In most types of industrially manufactured products there are usually one or more joints present. These joints could be made using many joining procedures including welding. Independent of joining procedure however, the homogeneity and mechanical strength of the joints in a product tend to influence the lifetime and overall performance of the product itself to a great extent.

In order to achieve optimum productivity when manufacturing a certain product and also optimum performance of the product itself it is of great importance to choose a favourable geometry of joints in the product and also to minimise the presence of defects in these joints. This is valid independently of the joining procedure(s) chosen. Today, the knowledge is however often limited regarding ways of minimising the occurrence of defects in a joint.

This will, from time to time, cause difficult quality problems in the manufacturing industry and also prevent/delay the implementation of interesting joining procedures. A well-known example here is the Lack Of Fusion (LOF) problem in Metal Inert Gas/Metal Active Gas (MIG/MAG) welding which has given this joining method a very bad reputation in demanding applications such as pressure vessels.

Other examples are laser welding and Friction Stir Welding (FSW) where quite little is known about which parameters that rule both the general level of mechanical strength (both static and dynamic) and the presence of defects in the joint for a certain application.

The joining procedures can, roughly, be divided in two main groups:

1. Joining where the ingoing base materials melt and mix together and then solidifies to a joint. All types of conventional fusion welding methods such as Manual Metal Arc (MMA), ("stick electrodes"), MIG/MAG and laser welding etc. belong to this group.

2. Joining where the ingoing base materials do not melt. Different types of brazing methods belong to this group as well as FSW, Magnetic Pulse Welding (MPW), ultrasonic welding, etc. With the exception for FSW the ingoing base materials in the joint will not be mixed when using joining procedures in this group.

The joining methods discussed in this thesis are two from group one, MIG/MAG- and laser welding and one from group two, Friction Stir Welding (FSW).

MIG/MAG-welding is the single most used fusion welding method today but has until now had a bad reputation in the manufacturing industry for applications with stringent quality demands such as pressure vessels. The bad reputation is mainly caused by so called Lack Of Fusion (LOF) defects which are said to occur more frequently with MIG/MAG than with other common fusion welding methods (MMA, Tungsten Inert Gas (TIG), Submerged Arc Welding (SAW) etc.). In this thesis, different aspects around the LOF-problem in MIG/MAG-welding are discussed. Counteractions are also proposed.
FSW is a relatively new (~10 years old) joining method, which has gained a good reputation especially for applications in aluminium alloys. Even here though, LOF and other types of defects occur from time to time. Mechanisms for formation of some of these defects and also the influence of the geometry of the joint on the fatigue strength are discussed.

Laser welding is a joining method that has gained much interest especially for thin sheet applications mainly due its very high productivity. However, different types of defects occur here also from time to time which tend to limit both the implementation and the productivity to a great extent. In this thesis, different quality aspects around laser welding are discussed together with the mechanical properties (formability and static tensile strength) of laser welded joints.

2. PURPOSE

The main purpose with this thesis is to increase the understanding for the formation of some common defects in FSW, MIG/MAG- and laser welding. Another purpose is to show the role of the geometry of a welded joint on its fatigue strength and quality level.

3. LITERATURE REVIEW

The purpose with this literature review is to give a brief overview over the areas mentioned above with a special focus on the welding methods FSW, MIG/MAG- and laser welding.

3.1 Friction Stir Welding (FSW)

The principle for Friction Stir Welding (FSW) is that a special rotating tool creates heat and mixes together the materials to be joined, see Fig. 1. The process is characterised by very high strain rates and relatively low temperatures (~0.8*melting temperature in K) in the welding zone, which gives unique structures in the weld.
The grain size for an example is much finer in the welded zone compared with the parent material, see Fig. 2, which is unique for a welding process. The welded zone will therefore have much more favourable properties (higher toughness etc.) compared with conventional fusion welding methods such as MIG/MAG, MMA, TIG etc. The geometry of a FSW-weld is also much different from a conventional weld, see Fig. 3, with smooth transitions between the parent material and the weld.
Due to the intense physical mixing of the materials to be joined the occurrence of different kind of common welding defects (pores, slags, LOF, cracks etc.) are reported to be much lower compared with conventional fusion welding methods such as MIG/MAG, MMA, TIG etc. [4], [7]. Due to the low occurrence of defects and the smooth transitions between the parent material and the weld, see Fig. 3, the mechanical properties (both static and dynamic) of FSW-welds is often reported to be superior (see Fig. 4) compared to conventional fusion welds (MMA, MIG/MAG, TIG etc.) [1], [4], [7].

The FSW process parameters can usually be varied a lot without creating defects, see Fig. 5. Serious defects can, however, occur with FSW if the process conditions are unfavourable. The most common types of defects in FSW-welds independent of joint type are reported to be cavities, see Fig. 7, and surface cracks, see Fig. 5 [2], [5] and [6].
In FSW-lap joints, LOF-like defects between the sheets to be joined occur from time to time, which reduces the effective thickness of the joint, see Fig. 6 [5]. The occurrence of defects in FSW-welds is generally reported to be related both to the choice of FSW-tool geometry and process parameters (rotation speed, traverse speed, down force etc.) [5], [6]. Typical influence of the FSW-tool geometry on the occurrence of cavities is shown in Fig. 7 [6].

![Process Window for FSW in Aluminium (AA 1100, t=6mm), FSW-Weld Appearance (Right), Please Notice that only Weld (c) is of unacceptable quality due to a Centre Crack [2](image)](image)

Fig. 5. Process window (left) for FSW in aluminium (AA 1100, t=6mm). FSW-weld appearance (right), please notice that only weld (c) is of unacceptable quality due to a centre crack [2].

![Typical Appearance of LOF-Like Defects (marked with arrows) in FSW-Lap Joints [5](image)](image)

Fig. 6. Typical appearance of LOF-like defects (marked with arrows) in FSW-lap joints [5].

![Cavity (marked with an arrow as "pores" in the upper figure, a close-up is shown to the right) in a FSW-butt weld in 4 mm aluminium (AA 2024-T3), notice the the positive influence of the tool change from A to B [6](image)](image)

Fig. 7. Cavity (marked with an arrow as “pores” in the upper figure, a close-up is shown to the right) in a FSW-butt weld in 4 mm aluminium (AA 2024-T3), notice the the positive influence of the tool change from A to B [6].
Different types of tool geometries are shown in Fig. 8. It should be noticed that it is often necessary to develop a new tool design for each welding situation in order to obtain optimum productivity and weld quality.

![Different types of tool geometries](image)

Fig. 8 Different types of tool geometries [4]

Finally, it can be concluded that FSW is a welding method capable of giving joints of a very high and consistent quality if correct choices of FSW-tool geometry and process parameters are made. The FSW-process seems to be very robust with a large process parameter window compared to conventional fusion welding processes (MMA, MIG/MAG, TIG etc.).

### 3.2 MIG/MAG

#### 3.2.1 General technical description

The principle for the Metal Inert Gas/Metal Active Gas (MIG/MAG) welding process is that a continuous electrode with automatic feeding and a base metal of a work piece are melted together by an arc. An externally supplied gas shields the whole process. This process can be either semiautomatic or automatic and it consists of the following basic equipment, see Fig. 9 [8], [9].
1. Power source
2. Supply of shielding gas
3. Wire spool
4. Welding control unit
5. Wire feed motor and associated drive rolls
6. Welding gun
7. Work piece

*Fig. 9 Basic equipment and process in MIG/MAG welding [8], [9]*

There are two types of electrodes used in MIG/MAG welding, solid wire electrodes and cored wire electrodes. The cored wires can either be filled with flux or metal powder. A very important feature when choosing an electrode is that the deposit matches the physical and mechanical properties of the base metal.

The shielding gas plays two important roles in MIG/MAG-welding. The first role is to protect the molten metal in the weld pool from the influence of the surrounding atmosphere. Without proper gas protection the metals in and adjacent to the weld pool will easily form oxides and nitrides, which can cause serious weld defects like LOF and also have a detrimental effect on the mechanical properties of the weld deposit. The second role is to affect the welding properties (penetration profile of the weld bead, arc type etc.) in the desired way (see Fig. 10) [8]
The shielding gas can be either inert or active, depending on the filler and base metal used.

- **Non-ferrous metals ⇒ Inert gases** (MIG welding) [8], [9], [10]

Inert gases like argon and helium and mixes of the two produce excellent weld results for non-ferrous metals like for example aluminium, magnesium and copper, see table 1.

<table>
<thead>
<tr>
<th>Density</th>
<th>Thermal conductivity</th>
<th>Arc stability</th>
<th>Spatter/weld appearance</th>
<th>Arc type</th>
<th>Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar + 1.4×air ⇒ heavier and more effective than He</td>
<td>-</td>
<td>+ more stable due to a lower voltage</td>
<td>+/-</td>
<td>+ spray, in the normal operating range ⇒ preferable</td>
<td>-</td>
</tr>
<tr>
<td>He -</td>
<td>+ Arc energy more uniformly dispersed ⇒ different weld bead profile</td>
<td>-</td>
<td>+/- a deep, broad, parabolic weld profile ⇒ good</td>
<td>-</td>
<td>+ Increased productivity, decreasing pore formation</td>
</tr>
</tbody>
</table>

**Table 1: Comparison of properties of inert gases used in MIG welding**

- **Ferrous metals ⇒ Inert + Active gases.**

When welding ferrous metals these inert gases fail to produce the best possible conditions while the arc tends to be erratic. This manifests itself through spatter or undercutting when using pure helium or argon respectively. To achieve the best possible weld quality, additions of O₂ or CO₂ can to be made to the argon. The chemical behaviour when adding these active gases is oxidizing, how much depends of course on the amount of O₂ or CO₂. For carbon and low alloy steels CO₂ in its pure form can used. A higher penetration and a lower overall cost are reasons for this usage. Negative aspects though are the oxidizing nature of the arc and that much coarse spatter can be observed [8], [9], [10].

- 12 -
There are two traditional arc types used in MIG/MAG-welding and these are spray-arc and short-arc. As can be seen in Fig. 11, there are also modes in which the arc is less stable like for example in the globular arc mode or when the voltage is too low [8], [9], [10], [11].

![Arc types for different current and voltage](image)

*Fig. 11 Arc types for different current and voltage [10]*

-Spray arc

This arc type is characterised by a metal transfer where small droplets of a size equal to or less than the electrode diameter are transferred without causing short-circuiting see Fig. 12. The arc is very stable, which results in little spatter and a weld bead with a relatively smooth surface [8], [9].

For a given electrode diameter a minimum current and voltage is required to obtain the spray transfer mode. Therefore more heat is induced into the work piece compared to short arc. To get a good spray arc the appropriate shielding gas consists mostly of argon and no more than 25% CO₂ or O₂ [8], [9].

![Spray transfer](image)

*Fig. 12 Spray transfer*
- Short arc

For this arc type, the metal is transferred when the electrode is in contact with the molten weld pool on the work piece, see Fig. 13. The heat input is low and therefore the weld penetration is shallow. It is not always easy to have a totally stable arc and if for example the short-circuiting current is too high, spatter occurs and the characteristic short-arc sound is disrupted.

![Fig. 13 Short arc](image)

- Globular arc

In this mode, which is a mixed mode that is very sparsely used, the arc is in the form of irregular big droplets, see Fig. 14. This results in much spatter and a surface that is rough in appearance. This can be somewhat reduced when using CO2 or He as a shielding gas [8], [9].

![Fig. 14 Globular transfer](image)
3.2.2 **Weld defects in MIG/MAG-welding - general**

In the following text some of the most important weld defects in MIG/MAG-welding are described. Acceptance criteria for each weld defect according to one of the most well known weld quality standards, ISO 5817 ed. 1 [25], are also given. In this standard three different weld quality levels (B, C and D) are defined where B is the most stringent level. Level B is often applied when the demands on the finished weld are high. Common examples here are pressure vessels and aerospace applications.

3.2.3 **Root defects [15], [25]**

This type of weld defect is more common with MMA and MIG/MAG with cored electrodes than with other welding processes. In ISO 5817 ed. 1 root defects are regarded as a serious weld defect which is not accepted at all in level B (most stringent) and only to a very small extent in the less stringent levels C and D. A root defect can also induce other serious weld defects, such as a solidification crack, which is shown in Fig. 15.

![Typical root defect in a MIG/MAG-weld (bottom part of the Figure) which also has induced a solidification crack (mid part of the Figure), please notice the severe plate edge misalignment [15]](image)

Fig. 15 Typical root defect in a MIG/MAG-weld (bottom part of the Figure) which also has induced a solidification crack (mid part of the Figure), please notice the severe plate edge misalignment [15]

Root defects in MIG/MAG-welds can be caused by several reasons of which the most common are mentioned below.

- Too small heat input (too low weld current/too high travel speed)
- Unfavourable torch position relative the root area in the joint (torch positioned on one of the side walls of the joint instead of in the middle of the bottom area of the joint)
- Too narrow joint configuration (too small gap width/too small joint angle)
- Plate edge misalignment (see Fig. 15 and 17) or varying gap width

Counteractions against this type of weld discontinuity are proposed in the following statements.

- Increase the heat input (increase the weld current and/or decrease the travel speed)
- Use a favourable torch position (in the middle of the bottom area of the joint)
- Make the joint wider (increase the gap width and/or increase the joint angle), it must be noticed here however that too big a gap width can increase the risk for solidification cracks, see 3.2.5. Gap widths in the range of 1-3 mm and V-joint angles in range of 50-60° are often recommended by the plate/filler material manufacturer.
• Minimise the plate edge misalignment and ensure that the gap width are constant along the weld. This is especially important in mechanised welding where the welding speeds usually are much higher and the adjustment of welding process parameters are less intuitive compared to manual welding. In other words, a skilled welder can usually compensate much easier than a welding machine for a varying gap width and plate edge misalignment.

This type of weld discontinuity is normally not dependent on the material type even if some nitrogen alloyed stainless steels can require a more wide joint than usual (V-joint angle of 70° instead of 50-60°). The occurrence of root defects is however to some extent depending on the operator (unfavourable choice of process parameters and/or torch position).

3.2.4 Lack of fusion [11]-[27]

Lack of fusion (LOF) is a serious type of weld defect that can occur under certain conditions with nearly all types of fusion welding methods. In MIG/MAG, LOF has however been reported to occur more often compared with other common welding methods such as MMA- and TIG-welding.

In ISO 5817 ed. 1 LOF is regarded as a serious weld defect which is not accepted at all in level B-C and only to a very small extent in the least stringent level D. Typical appearance of LOF in two different types of MIG/MAG-welds are shown in Figs. 16-17. In these Figs. the nature of LOF as a planar or semi-planar weld defect is clearly shown. This fact often makes this type of weld defect harder to detect with NDT compared to other types of weld defects.

![Fig. 16 Typical LOF in a single pass MIG/MAG-weld (black vertical line to the right of the weld)](14)
LOF in MIG/MAG-welds can be caused for several reasons of which the most common ones are mentioned below.

- Too small heat input (too low weld current/too high travel speed)
- The arc type seems to have an important influence on the occurrence of LOF especially for thicker plate (> ~8 mm). A lot more LOF has been reported when using short arc instead of spray arc in 8 mm plate [3].
- Too much molten material in the joint and/or too low travel speed which can cause the molten material to advance before the weld arc and cause LOF. This phenomenon is most likely to occur in unfavourable welding positions such as vertical/inclining down, see Fig. 18.
- Unfavourable torch position in relation to the welding position is also important in unfavourable welding positions such as vertical/inclining down. An unfavourable torch position in for example inclining down welding position will make it easier for the molten weld metal to advance before the weld arc and cause LOF.
- Too narrow joint configuration (too small gap width/too small joint angle).
- Positioning the torch against the thinner plate when welding in joints with a big difference in plate thickness.
Counteractions against this type of weld defect are proposed in the following statements.

- Use higher heat input (increase the weld current and/or decrease the travel speed)
- Balance the wire feed speed in relation to the travel speed
- If possible, avoid short arc when MIG/MAG-welding in thicker plates (> ~8 mm).
- Use a favourable torch position in relation to the welding position. A backhand torch position, see Fig. 19, is usually most favourable especially in vertical/inclining down welding positions. This can be understood by the fact that the arc pressure will help to “push up” the molten material in the joint and therefore prevent the molten material to advance before the weld arc.
- Make the joint wider (increase the gap width and/or increase the joint angle), it must be noticed here however that too big gap width can increase the risk for solidification cracks. Even here, gap widths in the range of 1-3 mm and V-joint angles in range of 50-60° are often recommended by the plate/filler material manufacturer.
- Position the torch against the thicker plate when welding in joints with a big difference in plate thickness.
This type of weld defect is normally not dependent on the material. The occurrence of LOF is however highly dependent on the operator especially in manual MIG/MAG. Even if this type of weld defect still is regarded as frightening it could in most cases be avoided if proper measures are taken and a qualified welding procedure is used.

3.2.5 Solidification cracks [15], [25], [28]

This type of defect can occur with all fusion welding methods. In ISO 5817 ed. 1 all types of cracks except microcracks (height x length < 1 mm²) are regarded as serious weld defects which are not accepted at all in any of the quality levels B, C or D. Solidification cracks are often surface breaking, see Fig. 20, but could also be non-surface breaking, see Fig. 21.
Solidification cracks in welds can be caused by several factors of which the most common are mentioned below.

- The chemical analysis of the base material and/or filler material. High levels of impurities such as sulphur and phosphorous are in general unfavourable. A high carbon and niobium content will also promote this type of cracks in carbon steels. Manganese and silicon can, on the other hand, help to decrease the risk for this type of cracks in carbon steels. The following cracking index for assessment of the probability of solidification cracking in submerged arc welds in carbon-manganese steel has been developed by Bailey and Jones [28]:

$$U_{CS} = 230C + 190S + 75P + 45Nb - 12.3Si - 5.4Mn - 1$$

- The amount of each element, C etc, are given in mass%. Solidification cracking of fillet welds is likely if $U_{CS} > 25$. Weld pass/joint shape and other factors mentioned further in this work may alter the risk for solidification cracks to some degree. The solidification mode also plays an important role here. A ferritic-austenitic solidification is known to give the best resistance to solidification cracking while pure austenitic solidification will promote solidification cracking. Pure austenitic solidification occurs in certain high alloyed stainless steels and nickel base alloys.

- Unfavourable width/depth ratio (<1) of the weld pass and/or joint
- Too high degree of restraint of the joint. This can be caused by too high heat input, severe forming operations, thick plates and heavy clamping.
- Too big gap width.
Counteractions against this type of weld defect are proposed in the following statements.

- Choose base and filler material with documented resistance to solidification cracking.
- If possible choose welding data and/or joint configuration in such a way that a width/depth ratio > 1 of the weld pass and/or joint is obtained.
- Minimise the degree of restraint of the joint by for example not using too high heat input and too heavy clamping.
- Only use a gap width big enough to avoid root defects and lack of fusion. The plate/filler material manufacturer usually recommends a gap width of 1-3 mm.

This type of weld defect is highly dependent on the material type. Certain nickel base alloys, aluminium alloys and high alloyed stainless steels are sensitive for this cracking mechanism. Other materials can also be sensitive if they contain high levels of impurities such as sulphur and phosphorous. The occurrence of solidification cracks is however only to a small extent depending on the operator (heat input, clamping etc.).

3.2.6 Porosity [23], [25]

This type of defect is more common with MIG/MAG and SAW compared with other welding processes. Porosity is however not regarded as a serious weld defect unless the amount of and/or size of the pores exceed high levels. In ISO 5817 ed. 1 local clusters of spherical pores are accepted to a quite high degree in all three quality levels B, C and D (4%(level B)-16%(level D) of the projected weld area). Elongated pores are only accepted in the least stringent level, D. Pores could both be surface breaking or non-surface breaking, see Fig. 22.

![Fig. 22 Porosity in a MIG/MAG-weld in aluminium [23]](image-url)
Porosity in MIG/MAG-welds can be caused for several reasons of which the most common are mentioned below.

- Dirt (oil, grease etc.), rust and/or humidity on the surface of the material to be welded
- Welding of Zn-coated and/or painted material especially in lap joints
- Insufficient shielding gas protection of the weld area caused by turbulent/disturbed shielding gas flow, too low shielding gas flow or impurities in the shielding gas itself. Turbulent/disturbed shielding gas flow can be caused by wind, too high shielding gas flow or adhering spatter in the shielding gas nozzle. Impurities in the shielding gas itself are usually caused by leakage of air and/or humidity into the shielding gas system. This is in turn usually caused by defective/unsuitable hoses and/or couplings and more seldom by contaminated gas in the bottle.

Counteractions against this type of weld defect are proposed in the following statements.

- Clean the plates from dirt, rust, humidity and/or paint prior to welding.
- Use only dedicated filler materials and welding procedures when welding Zn-coated material especially for lap joints.
- Do not weld in wind.
- Use a properly adjusted shielding gas flow for each welding situation (not too low or high), see for recommendations given by the welding material and/or gas supplier.
- Check hoses and couplings regularly for leakage. Be sure that hoses and couplings are of a suitable type. Even here it is a good idea to see for recommendations given by the welding material and/or gas supplier.
- Keep the shielding gas nozzle clean from adhering spatter.

This type of weld defect is to some extent dependent on the material type. Porosity often occurs in aluminium alloys, Zn-coated materials and certain high alloyed stainless steels. Independent on material type, porosity often occurs using MIG/MAG at high data with flux cored filler wires. The occurrence of porosity is however only to a limited extent depending on the operator.
3.2.7 Spatter [9], [10], [24]

This type of defect is more common with MIG/MAG and MMA compared with other welding processes. Like porosity, spatter is however not regarded as a serious weld defect unless the amount of and/or size of the spatter exceeds high levels. In ISO 5817 ed. 1 spatter is accepted in all three quality levels B, C and D. If spatter could be accepted or not is dependent on the application in each case. Spatter is a typical surface defect, see Fig. 23.

![Fig. 23 Spatter on a MMA-weld](image)

Spatter on MIG/MAG-welds can be caused by several factors of which the most common are mentioned below.

- Unsuitable choice of shielding gas for the chosen combination of base/filler material and arc type. High CO\textsubscript{2} – content in the shielding gas will in combination with high welding current give more coarse adhering spatter.
- Unsuitable choice of welding process parameters/conditions which can give unstable and/or too long arc which in turn will give much spatter.
- Unsuitable filler material.
- Contaminated filler material (dirty, greasy etc.)

Counteractions against this type of weld defect are proposed in the following statements.

- Choose a suitable shielding gas and filler material. Use recommendations given by the supplier of filler material/gas.
- Use suitable welding process parameters/conditions.
- Use only clean filler material.
- Changing from a stationary arc (short arc or spray arc) to a pulsed arc can in some cases be very helpful in order to promote spatter.

This type of weld defect is dependent both on the material/gas type and the operator (process parameters).
3.2.8 Concluding remarks

Metal Inert Gas/Metal Active Gas welding (MIG/MAG) is a relatively new fusion welding process that was introduced on the market in the mid 1950:s. It has become the single most used fusion welding process in the manufacturing industry today. The reasons for this are several but one of the most important are a relatively high productivity compared to Manual Metal arc Welding (MMA) and other manual processes (Tungsten Inert Gas welding (TIG), oxy-acetylene, etc.). The process is also flexible and easy to implement in mechanised welding stations (robot cells etc.). When the process was new it was also considered to be easy to learn and use compared to other fusion welding processes.

Very soon however, it turned out that some types of weld defects seemed to be more common with the MIG/MAG process compared to other fusion welding processes. This is especially the case for lack of fusion (LOF) which is a serious weld defect that can have a major influence on the structural integrity of a construction. For many years the MIG/MAG-process had a bad reputation for demanding applications such as pressure vessels. The understanding for why and when LOF occurred was also limited.

During the last decade however, there have been several technical improvements, which has lead to a better reliability of the MIG/MAG-process regarding the occurrence of LOF as well as other weld defects. Recent research work has also helped to increase the understanding for the occurrence of LOF.

3.3 Laser welding

The abbreviation LASER stands for Light Amplification by Stimulated Emission of Radiation which means that the atoms in a media are stimulated to emit radiation at a certain wavelength. In contrast to ordinary light which consists of a mix of wavelengths laserlight consists of only one wavelength. Laserlight is also much less divergent than ordinary light. These properties make it possible to focus the laser light into a very narrow (~Ø 0.3 mm) focal spot. The power density (MW/cm²) in a laser beam can be extremely high and exceeds all ordinary welding processes by a factor of 100-1000. Due to the low divergence a laser beam can also travel a long distance without significant loss of power density.

The high power density and low divergence makes it possible to cut with very high precision and speed or make welds with a very high travel speed and/or very high deep/width-ratio (high penetration/very narrow beads). The travel speeds in laser welding are often 5-10 times higher than in conventional fusion welding (MIG, TIG etc.) [29].

Until some years ago the main drawback of lasers was the fact that laser sources for industrial use were very expensive and did not have enough power to be economically justified compared with conventional welding and cutting techniques.

During recent years however it has become economically and technically possible to use high power (> 3 kW continuous) lasers in an industrial environment for welding and cutting.

There are many types of lasers on the market today but when a high power (>3 kW) continuous laser is needed only two types of lasers are of interest. These two types are the CO₂ laser and the Nd:YAG laser. The CO₂ laser is the most powerful of all commercial laser
sources on the market today and capable to deliver up to 45 kW in a continuous wave (cw). The most powerful cw Nd:YAG lasers on the market can deliver up to approximately 5 kW.

The two lasers mentioned above have advantages and disadvantages that make them suitable for different metals and welding situations. This is discussed below.

3.3.1 Laser types - The CO₂-laser

In the CO₂ laser the laser beam is generated by creating an electrical discharge in a glass cavity containing a gas mixture consisting of CO₂, He and N₂. The wavelength of the emitted radiation is 10.6 μm which corresponds to medium infrared (IR). Via a set of mirrors the beam is directed from the laser cavity to the work piece. As mentioned before this laser type is capable of delivering the highest power of all commercially available laser sources (45 kW). This laser type also gives most power per cost unit. The beam quality is usually very good.

Most common metals can be welded without problems with a CO₂ laser except those with a surface which has a very high reflectivity for radiation with a wavelength of 10.6 μm, see Fig. 24, such as copper and aluminium. A disadvantage with this laser type is the fact that the equipment is often quite bulky which can make it hard to implement the technique in robot cells.

![Fig. 24 Surface reflection as a function of wavelength [32]](image-url)
3.3.2 Laser types - The Nd:YAG-laser

In the Nd:YAG (Neodymium Yttrium Aluminium Garnet) laser the laser beam is generated by sending light from arc lamps or discharge tubes and diodes into a solid body which consists of a special garnet crystal made of yttrium and aluminium doped with neodymium. The wavelength of the emitted radiation is 1.06 \( \mu \text{m} \) which corresponds to near infrared (IR). The beam can be directed from the laser source to the work piece with a set of mirrors or with an optical fibre.

The maximum power for commercially available continuous Nd:YAG lasers is 5 kW. The cost for a Nd:YAG laser is usually higher than for a CO\(_2\) laser of the same output power.

An advantage with this laser type is the possibility to use an optical fibre with a length of several tens of meters to carry the beam from the laser source to the work piece. This makes it easy to implement the technique in robot cells [30].

This laser type is also more suitable than a CO\(_2\) laser for welding in materials with a highly reflective surface such as aluminium and copper. This is mainly due to the lower surface reflectivity at the emitted wavelength (1.06 \( \mu \text{m} \)), see Fig. 24, compared with the reflectivity at the wavelength of 10.6 \( \mu \text{m} \) that is emitted from a CO\(_2\) laser.

3.3.3 Shielding gases

Some type of shielding gas is usually needed in laser welding in order to protect the weld pool from oxidation.

The most commonly used shielding gas for welding with a CO\(_2\) laser is pure helium and mixtures consisting of up to 70% argon in helium. The use of pure argon at laser powers > 3 kW tends to decrease the maximum possible welding speed significantly especially for higher material thickness i.e. in the lower welding speed range. In some cases with low gas flow rates the welding process even becomes impossible due to formation of a highly absorbing shielding gas plasma [29].

The most commonly used shielding gas for welding with a Nd:YAG laser is pure argon. There is hardly no risk at all to form a highly absorbing shielding gas plasma with a Nd:YAG laser which hence gives freedom in the choice of shielding gas [29].

Some type of gas nozzle is necessary in laser welding in order to create a “blanket” of shielding gas that protects the weld pool from oxidation during welding. The most common types of gas nozzles are presented in Fig. 25.
The coaxial nozzle, ring nozzle and side tube are common in laser welding and their application depends on the requirements in the specific welding situation.

A side tube is often necessary when a cross-jet\(^1\) is required to protect the focusing optics from spatter. This is often the case for high power Nd:YAG lasers.

The plasma jet nozzle is sometimes used at high power (> 5 kW) CO\(_2\) laser welding together with pure helium and other shielding gases and makes it easier to avoid formation of a highly absorbing shielding gas plasma [29].

*Remark: 1) A cross jet is a stream of compressed air that is passing transverse to the laser beam on the outside of the optics. The purpose with this is to protect the optical system from weld spatter.*

3.3.4 *Filler material*

The use of filler material in laser welding is only limited to special cases in order to avoid problems with sagging, porosity and/or cracking. These problems are usually most pronounced when welding certain kinds of aluminium alloys.
3.3.5  Weldability- weld defects - General

Independent of material and laser type, the most common defects type in laser welding are linear misalignment and incompletely filled groove, see Fig. 26. Another common weld defect in laser welding is lack of fusion, see 3.2.4 for reference. These three weld defects are well known in the manufacturing industry and are mainly caused by the fact that the laser beam is very narrow and that the travel speed is very high compared to conventional fusion welding processes. Small deviations in the material alignment and the positioning of the welding head will therefore have a great influence of the weld quality.

In order to prevent the above mentioned defects it could be effective to defocus the laser beam to a wider spot, use filler metal and to decrease the welding speed. These measures will, however, also decrease the productivity, perhaps to a non-acceptable level. Other weld defects that can occur in laser welding are porosity, blowholes, solidification cracks and cold (hydrogen) cracks. These weld defects are however more dependent on the chemical analysis of the material to be welded than the laser welding process parameters. This is described in more detail as follows.

Fig. 26: Linear misalignment + incompletely filled groove, DP600 steel(uncoated), t=1.25 mm, 6 kW CO₂, travel speed 5.5 m/min [45]

3.3.6  Ferritic carbon steels

Most types of common ferritic carbon steels have a good weldability with laser independent of laser type. There are, however, a few limitations which are described below.

Due to the rapid thermal cycle the hardness in the weld metal and /or HAZ can be substantially higher than for other welding processes due to the formation of martensite. This makes the weld joint much less ductile and more susceptible for hydrogen cracking which put strict requirements on the surface cleanness and the gas protection.

For steels which have a carbon content over 0.25-0.30 wt% the hardness in the welded joint can be so high that it is very difficult to avoid cold cracking without preheating and post weld heat treatment even if the hydrogen levels are kept to a minimum [31], [34].
Steels of thickness > 10 mm also often suffer from a special type of centre crack when laser welded [33], [41], [43], [44], see Fig. 27. The only way to avoid this type of cracking is to reduce welding speed and/or make a V/U-groove preparation and weld with filler material [44]. There are also indications that the steel composition has an effect on the susceptibility for centreline cracking in this thickness range [43].

![Crack](image)

*Fig. 27 Centre crack [41]*

### 3.3.7 Zinc coated material

The weldability of zinc coated material is related both to the joint design and the thickness of the zinc layer. Butt joints are usually easy to weld without problem regardless of the thickness of the zinc layer [46]. Lap joints are much more difficult especially if the zinc layer thickness exceeds 7-10 μm [42]. Some type of gap is usually necessary in a lap joint in order to avoid pore formation and/or blow holes [42].

### 3.3.8 Stainless steels - General

There are many types of stainless steels on the market today developed for use in corrosive environments. The corrosion resistance of these steels relies on a thin chromium oxide layer which protects the metal from corrosion attack.

In welding this protecting oxide layer is easily destroyed by further oxidation if the weld pool is not protected from the oxygen in the surrounding air. In order to obtain the best possible corrosion resistance for a laser welded joint in stainless steel it is therefore advisable to use a good root gas protection device and mostly a gas shoe attached to the welding head. It is also important to have a good edge preparation free from oxides from thermal cutting operations.

Specific aspects regarding the weldability for each type of stainless steel are discussed as follows.
3.3.9 Stainless steels - Austenitic

The composition of these steels varies in the range of (w%) 0.02-0.1 % carbon, 0-0.5 % nitrogen, 0-7 % molybdenum, 8-35 % nickel and 17-30 % chromium.

This type of stainless steel usually has a good weldability with both CO₂ and Nd:YAG lasers. Some high alloyed grades might be susceptible to hot cracking [39].

For certain types of high nitrogen alloyed austenitic stainless steels the use of nitrogen in the shielding gas can be beneficial for the properties in the weld metal [29], [39].

3.3.10 Stainless steels - Ferritic

The composition of these steels varies in the range of (w%) 0.05-0.25 % carbon and 13-30 % chromium.

This type of stainless steel is weldable with both CO₂ and Nd:YAG lasers but to less extent than the austenitic type. The weld joint in the higher alloyed grades has a low or very low ductility due to formation of hard martensite in the HAZ and weld deposit [39].

A post weld treatment can be helpful in order to obtain a more ductile weld joint. The problems with low ductility in the weld joint in this type of stainless steel increases with increasing carbon and chromium content. The use of nitrogen in the shielding gas is detrimental for the properties in the weld metal and should be avoided [29].

3.3.11 Stainless steels - Martensitic

The composition of these steels varies in the range of (w%) 0.1-1.0 % carbon and 13-18 % chromium and sometimes with different amounts of nickel and molybdenum.

This type of stainless steel is difficult to weld with both CO₂ and Nd:YAG lasers. The problems mentioned for ferritic steels in 3.3.10 are even more pronounced for this type of steel [39]. The ductility in the weld joint is usually so low that cold cracking takes place if no preheating and post weld heat treatment are performed. If the carbon content is higher than 0.1 w% a filler material is necessary to improve the ductility in the weld deposit and reduce the risk for cold cracks [39].
3.3.12 Stainless steels - Duplex

The composition of these steels varies in the range of (w%) 0.02-0.05 % carbon, 0-0.3 % nitrogen, 0-4 % molybdenum, 4-7 % nickel and 18-26 % chromium.

This type of stainless steel has a good weldability with both CO₂ and Nd:YAG lasers [38], [39]. However due to the rapid thermal cycle during welding special measures have to be taken in order to obtain a reasonable phase balance (30-70 % austenite) between austenite and ferrite in the weld metal. The only practical way to achieve this is by using a suitable filler metal [38]. In addition, a shielding gas with a high nitrogen content or even pure nitrogen can also be helpful [38], [39].

3.3.13 Aluminium and its alloys - General

Aluminium and its alloys are generally regarded to have a limited weldability especially with CO₂ lasers. The Nd:YAG-laser is regarded as the most suitable laser type for aluminium, see parts 5.3.1 – 5.3.2 in this thesis. Problems with porosity, hot cracking, process instability, blowholes, cavities and irregular roots are often reported [35], [36], [37].

The problems can however be kept to an acceptable level in many cases and are depending on the welding technique and the type of aluminium alloy. One example is the use of twin spot/dual beam technique which has been reported in [35] to be helpful in order to stabilise the welding process. Another way is to add filler metal [35].

There are two main categories of aluminium alloys:

- precipitation hardening alloys
- unalloyed aluminium and alloys without precipitation hardening

Based on guidelines from American Aluminium association (AA) aluminium alloys can be divided in the following groups based on the main elements in the alloy [40]:

<table>
<thead>
<tr>
<th>Description – main alloy element(s)</th>
<th>Precipitation hardening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Al (min. 99.9 w%)</td>
<td>No</td>
</tr>
<tr>
<td>Al-Cu</td>
<td>Yes</td>
</tr>
<tr>
<td>Al-Mn</td>
<td>No</td>
</tr>
<tr>
<td>Al-Si</td>
<td>No</td>
</tr>
<tr>
<td>Al-Mg</td>
<td>No</td>
</tr>
<tr>
<td>Al-Mg-Si</td>
<td>Yes</td>
</tr>
<tr>
<td>Al-Zn</td>
<td>Yes</td>
</tr>
</tbody>
</table>
3.3.14 Aluminium and its alloys - Pure Al and Al-Mn

Alloys in these groups are non precipitation hardening and are regarded to have a good weldability with both CO$_2$ and Nd:YAG laser [35], [36].

3.3.15 Aluminium and its alloys – Al-Mg

Alloys in this group are also non-precipitation hardening and are reported to have a good weldability with both CO$_2$ and Nd:YAG laser even if process instability can occur in some cases. Some grades are reported to be susceptible to hot cracking [11]. This susceptibility seems to be depending of the magnesium content with a maximum around 2 w% [36] and [37]. The use of filler metal can reduce the risk for hot cracking [35]. The static strength of the weld joint is often good in these alloys.

3.3.16 Aluminium and its alloys – Al-Cu, Al-Mg-Si and Al-Zn (precipitation hardening)

These alloys are precipitation hardening and are widely used as structural material due to their combination of good or very good mechanical strength and in some cases (Al-Mg-Si) good corrosion resistance [36].

Alloys in the Al-Cu and Al-Mg-Si groups have a reasonably good weldability with lasers but they are reported to be more susceptible to hot cracking than alloys in the pure Al and Al-Mn groups and to some extent alloys in the Al-Mg group [35].

Alloys in the Al-Zn group have a more limited weldability with lasers than other aluminium alloys and some grades containing copper are even considered to be unweldable [36].

Also for these alloys the use of filler metal is very advantageous in order to reduce the risk for hot cracking [35]. Worth mentioning is the fact that the static strength of the joint in “as-welded” condition in these materials is often 60-80 % of the parent material together with a low ductility [35], [37]. In order to obtain full mechanical strength and ductility of the joint a post weld heat treatment is necessary [35], [37].
3.3.17 Concluding remarks

It is no doubt that welding of conventional engineering materials with laser has a great potential in order to increase both productivity and weld quality.

During recent years the high power laser sources suitable for welding have become much cheaper than before which sometimes makes laser welding economically preferable compared with conventional welding processes.

Most materials can be laser welded with excellent results, even those which have limited weldability with conventional welding processes. It is also possible to perform joints which are dissimilar both in material thickness and/or material type with results unmatched by conventional welding processes [47]. Dissimilar joints are common in “tailored blanks” applications which is a concept that has been developed in the automotive industry [48].

The concept “tailored blanks” simply means that sheets of different thicknesses and/or material grades are welded together in a sheet intended for forming of a major component such as doors, roofs etc. in a vehicle. More or less due to the developments in laser technology the tailored blanks concept has been widely spread.

The main drawback for laser welding is the fact that the small size of the laser beam puts high demands on the positioning equipment, straightness of the base material and edge preparations in order to obtain a good welding result. If these variables are not observed properly weld defects like lack of fusion, improperly filled joint or misalignment will occur frequently. It must also be noticed that some material types, e.g. duplex stainless steels, are less suitable for laser welding.

Another drawback is that the use of the laser technique is limited only to mechanised high volume applications. This is mainly due to the big size of the equipment, high welding speeds, need of precision positioning and the security aspects.
4. SUMMARY OF INCLUDED PAPERS

4.1 MIG/MAG, paper 1

The results from paper 1 show that the occurrence of LOF/slag defects in the tested type of weld is strongly dependent on arc type, material type and plate angle, see Figs. 28-29. It must be noted that no LOF/slag defects were found in the welds that were welded in horizontal position (plate angle 0°).

![Average LOF/Slag in Carbon Steel (CS) and Stainless Steel (SS) Welds](image1)

**Fig. 28** LOF/Slag in carbon and stainless steel MAG-welds dependent of arc type.

![Plate Angle - LOF/Slag](image2)

**Fig. 29** LOF/Slag in carbon and stainless steel MAG-weld as a function of plate angle.
It is also interesting to notice that paper 1 describes that LOF in MIG/MAG-welding could occur both to too low heat input and excessively high input ("advancing weld metal"). This is described in more detail in the literature review in this thesis, see 3.2.4.

If the hypothesis given in paper 1 about “advancing weld metal” is correct the occurrence of LOF/slag defects would increase with increasing plate angle. The reason for that is that the molten weld metal is then influenced more by the gravity. This is actually supported by the results in paper 1, see Fig. 29.

From the results in paper 1 and the literature review in this thesis the following conclusions can be made about the LOF/Slag problem in MIG/MAG-welding:

- The LOF/Slag problem in MIG/MAG-welding is closely associated to welding in downhill position. When welding in horizontal position LOF/slag defects can easily be avoided.

- The arc type has a significant influence of the occurrence of LOF/Slag, Syray arc has been shown to work better than short arc.

- In order to avoid LOF in downhill MIG/MAG-welding it is important to balance the wire feed speed to the travel speed

4.2 Laser welding, paper 2

Generally, the results in paper 2 show that laser welding of high strength dual phase (DP) sheet steels can be performed with a very high and consistent quality level.

However, weld defects do occur in laser welding from time to time. The dominating types of flaws that are reported in paper 2 were incompletely filled groove and misalignment. No cracks or slag inclusions were detected in any of the welds.

An example from paper 2 shows the quality assessment of a typical weld, see Fig. 30. The quality assessment were made according to the international quality standard for laser welding, ISO 13919-1. In this standard three different quality levels, B, C and D are defined where B is the most stringent level. The quality assessment of each weld were based on results from both visual and X-ray examinations.
Electron and laser-beam welded joints, ISO 13919-1

ID number: 2.28
Focal length [mm]: 200
Weld speed [mm/min]: 11.5

<table>
<thead>
<tr>
<th>Imperfection designation</th>
<th>Quality level: DP 600 coated; r=1.2 mm, 0.8% CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crater edge</td>
<td>B</td>
</tr>
<tr>
<td>Crater crack</td>
<td>B</td>
</tr>
<tr>
<td>Porosity and Oxyacetylene</td>
<td>B</td>
</tr>
<tr>
<td>Localised cluster defect</td>
<td>B</td>
</tr>
<tr>
<td>Shrinkage cavity</td>
<td>B</td>
</tr>
<tr>
<td>Lack of fusion</td>
<td>B</td>
</tr>
<tr>
<td>Incomplete penetration</td>
<td>B</td>
</tr>
<tr>
<td>Undercut</td>
<td>B</td>
</tr>
<tr>
<td>Excess weld-metal</td>
<td>B</td>
</tr>
<tr>
<td>Excessive penetration</td>
<td>B</td>
</tr>
<tr>
<td>Linear misalignment</td>
<td>D</td>
</tr>
<tr>
<td>Sagging</td>
<td>B</td>
</tr>
<tr>
<td>Incompletely filled grooves</td>
<td>B</td>
</tr>
<tr>
<td>Root cavities</td>
<td>B</td>
</tr>
<tr>
<td>Total</td>
<td>D</td>
</tr>
</tbody>
</table>

Comments:
Generally weld qualifies to B level. Ends lower quality (D and C) due to linear misalignment and incompletely filled grooves.

Fig. 30 Quality assessment certificate of laser-beam welded joint in carbon steel. K1, K2 = Ends of joint; C = Centre of joint; M1, M2 = Intermediate positions of joint

At the ends of the joint imperfections such as "incompletely filled grooves" and "linear misalignment" were commonly found. In some cases lower quality levels were also found at intermediate positions in the joint, see Fig. 30. The reasons for these defects have been discussed in the literature review in this thesis and are probably due to small deviations in the joint preparation and/or laser beam positioning.

It can be concluded that an optimal weld quality in laser welding could only be obtained if the joint preparation is made carefully and that the accuracy of the laser beam positioning equipment is high.
4.3 Friction Stir Welding

4.3.1 Paper 3

The results from paper 3 shows that most of the welds were free from defects. Some of the welds were however found to contain lack of fusion and cavities, see Fig. 31.

![Image showing weld defect](image_url)

*Fig. 31 Weld with 3.6 turns/mm, cavity and lack of fusion*

Due to lack of sufficient data it was not possible in paper 3 to relate the presence of weld defects (lack of fusion and cavities) to the process parameters and choice of FSW-tool to a higher degree. The literature review in this thesis shows however clearly that the occurrence of these and other weld defects is related both to process parameters and choice of FSW-tool. If a favourable choice of tool and process parameters are made FSW seems to be a robust welding process that produces welds of a high and consistent quality.
4.3.2 Paper 4

In paper 4 it is shown that the fatigue strength of a FSW butt joint in aluminum could be high (90% of the static strength), see Fig 32. For lap joints however the fatigue strength is low (20-30% of the static strength), see Fig. 32.

![Rupture strength vs Cycles graph]

Fig. 32 Results from static tensile testing and fatigue testing of FSW-joints in mixed aluminium materials (High pressure die cast 46000 + extruded profile AA 6063)

Two possible explanations for these results can be identified:

1. It is a common fact that an overlap joint in itself has an unfavourable geometry from a fatigue point of view compared to a butt joint.

2. The choice of FSW-tool is extremely important in order to “stir up” the oxide film on the overlapping surfaces properly. With a poor tool the surface oxides are not “stirred up” which leaves an oxide film between the sheets that can act as a lack of fusion defect, see Fig. 31.

Finally it can be stated that FSW is able to produce joints with good static and dynamic strength even in “difficult” material combinations such as cast to profile material. It could also be concluded that the geometry of the joint itself will affect its fatigue strength to a great extent.
5. REFERENCES


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