MASTER'S THESIS

Hybrid Laser vs. MAG Welding

Fatigue Behaviour and Reengineering Analysis

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Hybrid Laser vs. MAG welding: Fatigue behaviour and reengineering analysis

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PREFACE

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Finally but not least, thank you with all of my heart to my family, and especially my wife, Lorena, for your understanding, support, patience, and presence throughout my time in Luleå, in spite of the great distance between us which was not always easy to handle.

Fernando Rodas Alfaya.
Luleå, December 2013

ABSTRACT

Nowadays automotive industry competence forces companies 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 new weld methods, so as to allow greater resistance and consequently to reduce the thickness of the component.

The main objective in this master's thesis is to determine the minimum thickness that guarantees an optimum structural integrity of a component used in the automotive industry by a company in Luleå (Sweden) reconsidering its manufacturing design, as well as economic benefits arising from that.

This thesis is divided up into two papers:

The first paper shows a study about influence of the welding method in the workpieces based in fatigue tests. Equipment used for tests is described with their characteristics, advantages and benefits. Finally, the results and conclusions of the fatigue tests realized in the workpieces are summarized.

The second paper shows the calculations and results of the minimum thickness and costs of the workpiece that guarantees an optimum structural integrity.

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INTRODUCTION

1. Motivation of the research

Global economy presses manufacturing companies to optimize their processes. In automotive industry the aim is to reduce weight and costs as well as improving efficiency and mechanical properties. To carry out that, it is necessary to operate in methods, materials, processes, equipment, etc.

In this thesis, welding method is analyzed to achieve better fatigue behaviour and reduce weight of a structural workpiece.

The development of welding technology to its present state is one of the most significant manufacturing achievements in this century. Power plants, super tankers, pipelines and ground vehicles are just a few examples of structures that are critically dependent on welding operations. Traditional welding processes, e.g. arc welding of various kind, are already well adapted by the manufacturer and got the trust on the mechanical strength of the joint. New welding technologies, e.g. laser or hybrid laser welding, are still struggling to gain acceptance from manufacturers even though research has often demonstrated higher mechanical strength than that of conventional arc welded joints. One important factor in improving the level of application of laser or hybrid laser welding is a fuller appreciation of the fatigue behaviour of the welds produced.

In this case, the workpiece is welded by MAG welding method. To get better properties reducing weight and cost, hybrid laser method is proposed and analyzed.

2. Methodological approach

The overall goal of the research was to check the best fatigue behaviour of the workpiece that was welded with laser hybrid weld instead of MAG weld. Once verified that the piece has better fatigue behaviour using hybrid laser welding, the thesis focuses on calculating the minimum thickness and cost of the workpiece that guarantees an optimum structural integrity.

In paper I, a study about influence of the welding method in the workpieces based in fatigue tests is carried out. Equipment used for tests is described with their characteristics, advantages and benefits. Finally, the results and conclusions of the fatigue tests realized in the workpieces are summarized.

In paper II, the calculations and results of the minimum thickness of the workpiece that guarantees an optimum structural integrity are shown with a final study about the costs of the different thickness.

3. Industrial case

This thesis is focused in a steel beam member exposed to torsional loading used in automobile structure. This piece is manufactured in a company in Luleå (see figures 3.1, 3.2, 3.3).

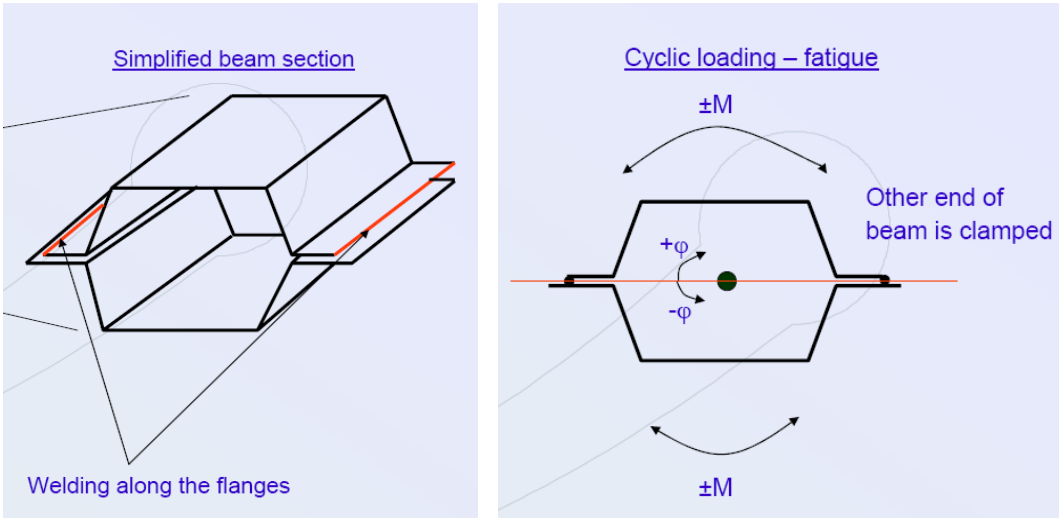

Figure 3.1: Beam member view

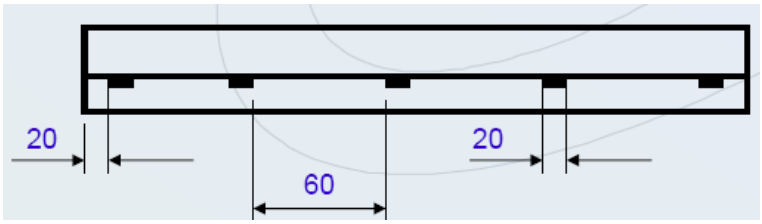

Figure 3.2: Measurements of intermittent MAG-Welding

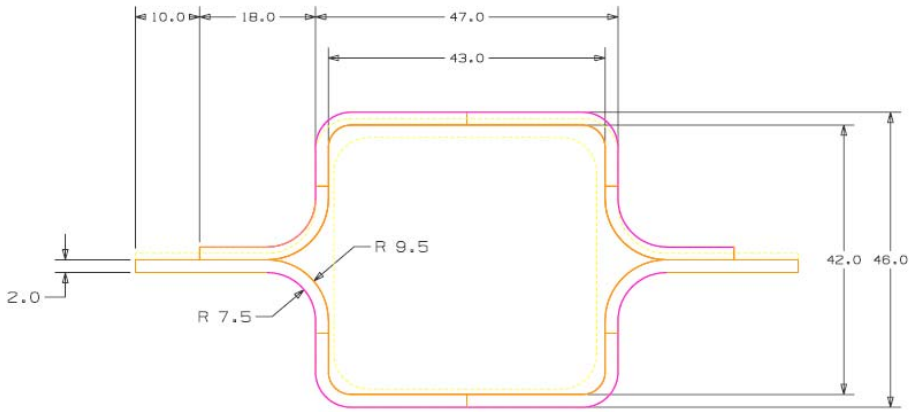

Figure 3.3: Cross section dimensions

4. Literature review

4.1 Welding

Welding is a fabrication process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the workpieces to form a bond between them, without melting the workpieces. It can be done using different energy sources, from a gas flame or electric arc to a laser or ultrasound.

The economics of joining a material may limit its usefulness. For example, aluminium is used extensively in aircraft manufacturing and can be joined by using adhesives or fasteners, or by welding. However, none of these processes has proven economical enough to allow the extensive replacement of steel by aluminium in the frames of automobiles. An increased use of composites in aircrafts is limited by an inability to achieve adequate joint strength.

Until the beginnings of the 20th century, welding was done via a process known as forge welding, which consists of heating up the pieces to be fixed together and then hammering them until they amalgamate. With the advent of electricity, the process became easier and faster, and it played an important part of the industry scene during World War I and II.

The use of welding in today's technology is extensive. It had a phenomenal rise since about 1930; this growth has been faster than the general industrial growth. Many common everyday use items, e.g., automobile cars, aircrafts, ships, electronic equipment, machinery,

household appliances, etc., depend upon welding for their economical construction [19].

Welding process is essential for the development of virtually every manufactured product. However, this process often appears to consume greater fractions of the product cost and to create more of the production difficulties than might be expected. There are a number of reasons that explain this situation.

- A very large percentage of product failures occur at joints because they are usually located at the highest stress points of an assembly and are therefore the weakest parts of that assembly. Careful attention to the joining processes can produce great rewards in manufacturing economy and product reliability.

- Welding difficulties usually occur far into the manufacturing process, where the relative value of scrapped parts is high.

- Welding is multifaceted, in terms of process variations (such as fastening, adhesive bonding, soldering, brazing, arc welding, diffusion bonding, and resistance welding) and in the disciplines needed for problem solving (such as mechanics, materials science, physics, chemistry, and electronics) [1].

One of the greatest difficulties for the manufacturing engineer is to determine which process will produce acceptable properties at the lowest cost because there are many fusion welding processes. Any change in the part geometry, material, value of the end product, or size of the production run, as well as the availability of joining equipment, can influence the choice of joining method. In this thesis will be studied two of these processes: MAG and Hybrid Laser welding.

4.1.1 GMAW Welding

Gas-Metal Arc Welding (GMAW) is an arc welding process that joins metals together by heating them with an electric arc that is established between a consumable electrode (wire) and the workpiece. An externally supplied gas or gas mixture acts to shield the arc and molten weld pool [1] (see figure 4.1).

Although the basic GMAW concept was introduced in the 1920s, it was not commercially available until 1948. At first, it was considered to be fundamentally a high-current-density, small-diameter, bare-metal electrode process using an inert gas for arc shielding. Its primary application was aluminium welding. As a result, it became known as metal-inert gas (MIG) welding, which is still common nomenclature. Subsequent process developments included operation at low current densities and pulsed direct current, application to a broader range of materials, and the use of reactive gases (particularly carbon dioxide) and gas mixtures. The latter development, in which both inert and reactive gases are used, led to the formal acceptance of the term gas-metal arc welding (see figure 4.2).

The GMAW process can be operated in semi-automatic and automatic modes. All commercially important metals, such as carbon steel, high-strength low-alloy steel, stainless steel, aluminium, copper, and nickel alloys can be welded in all positions by this process if appropriate shielding gases, electrodes, and welding parameters are chosen.

The most important advantages of this process are:

- This process can be used in every position when the proper parameters are used.
- Join a wide range of material types.
- Being that the electrode is a continuous wire it allows for long welds without stops and starts.

- GMAW has higher electrode efficiencies when compared to other welding processes.
- Welding speeds are higher than SMAW.
- Less operator skill is required.
- Is easily adapted for high-speed robotic, hard automation and semiautomatic welding applications.
- Lower heat input.
- Minimal post weld cleaning is required because a minimum of weld spatter and slag.
- GMAW offers the ability to easily bridge gaps in the joint. Not require high precision during edge preparation and setup.
- Excellent weld bead appearance.
- The GMAW process is a Low-Hydrogen process that makes it good for welding on materials that are susceptible to hydrogen cracking.

The GMAW process, like any welding process, has certain limitations that restrict its use:

- Due to the size of the GMAW gun it makes it hard to reach into smaller areas.
- There is a lot of heat that is radiated off the process that can cause discomfort.
- The Shielding Gas can be blown away from the weld pool causing many issues so welding arc must be protected.
- Relatively high levels of radiated heat and arc intensity can hinder operator acceptance of the process.
- The nature of the process prevents deep penetration welds. Joining thick sections often require multiple weld passes.

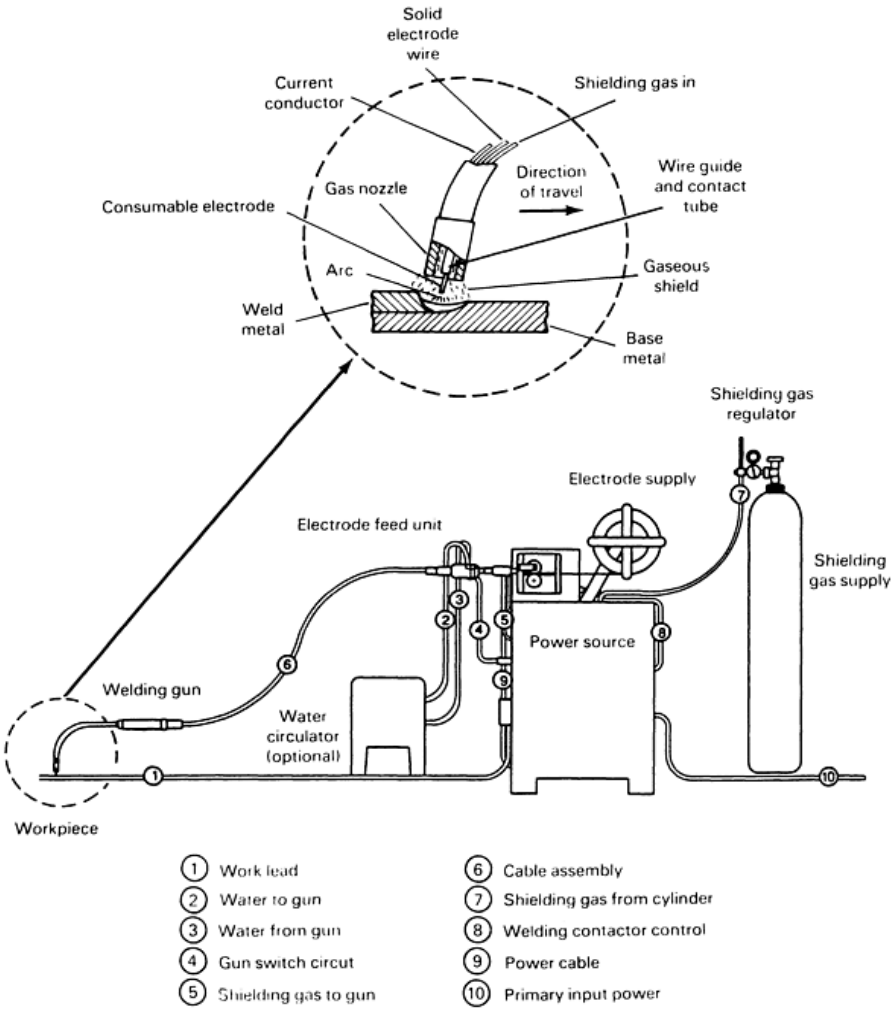

Figure 4.1: GMAW equipment [1]

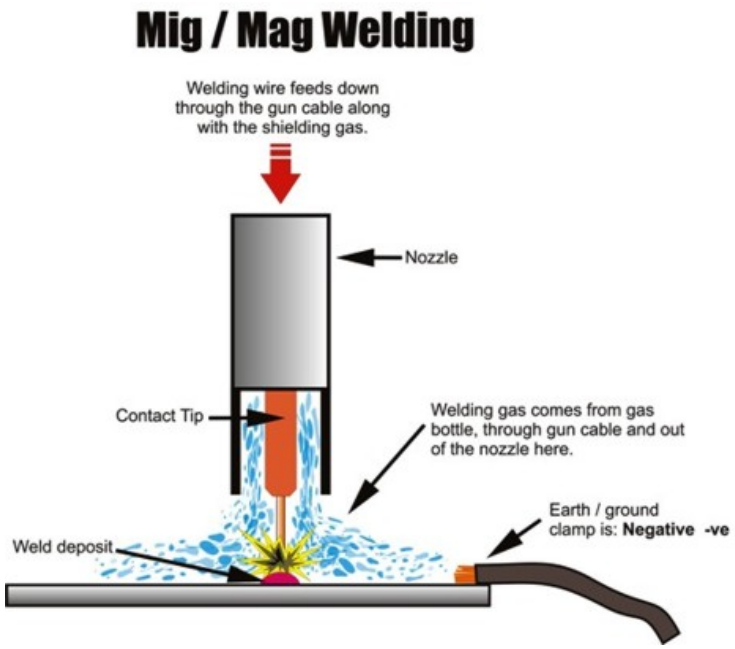

Figure 4.2: MIG / MAG Welding [19]

Shielding gas.

Shielding gases are inert or semi-inert gases that are commonly used in several welding processes. Their purpose is to protect the weld area from atmospheric gases, such as oxygen, nitrogen, and water vapour. Depending on the materials being welded, these atmospheric gases can reduce the quality of the weld or make the welding more difficult. Although weld metal properties are primarily controlled by the consumable composition, the shielding gas can directly influence the strength, ductility, toughness and corrosion resistance of a weld. [19]

Incorrect choice of a welding gas can lead to a porous and weak weld, or to excessive spatter; the latter, while not affecting the weld itself, causes loss of productivity due to the labour needed to remove the scattered drops.

A change in the shielding gas composition is usually considered an “essential variable” in most qualified welding procedures.

The primary gases used for electric welding and cutting are:

- Inert: argon (Ar), helium (He).
- Reactive: hydrogen (H_2), nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2).

The composition and purity of the gas or gas mixture should be tailored to meet the process, material, and application requirements. Shielding gases are used in either pure form or in blends of varying components. Therefore, the selection of a gas or gas mixture can become quite complex due to the many combinations available.

Three basic criteria are useful in understanding the properties of shielding gas:

- Ionization potential of the gas components.
- Thermal conductivity of the shielding gas components.
- The chemical reactivity of the shielding gas with the molten weld puddle.

The choice of shielding gas composition will have effect not only on shielding efficiency, but also on: electric arc properties (arc with, metal transfer type and arc stability), metallurgical processes in molten material (reaction with oxygen and combustion of alloying elements as well as reactions with nitrogen and carbon), technological welding parameters (some gasses allow higher welding speed, some demand surface cleaning of welded joint), welded joint characteristics (weld shape geometry, weld surface appearance, mechanical properties), environment pollution (emission of the combustion products). It is obvious from the above mentioned that the choice of shielding gas type also depends on mentioned criteria, among others on: base metal type, welding position and joint geometry, required metal transfer type, welded joint shape and appearance, acceptable costs, possibilities of supply etc.

MAG Welding.

Metal active gas welding (MAG) is, due to its good characteristics (above all flexibility and low price), one of the frequently used welding processes; in welding and surfacing in production, but also at reparation welding of most metal materials [1].

In MIG/MAG welding, the consumable metal electrode is both filler material and arc carrier. The shielding gas that flows out prevents chemical reactions between the hot workpiece surface and the surrounding air. This maintains the strength and durability of the weld metal. Inert and active gases can be used as shielding gases. Shielding

gases for welding are either inert or active. This is why we refer to metal inert gas (MIG) welding and metal active gas (MAG) welding.

Active gases react with the molten weld pool or the melting electrode and provide a greater opportunity to optimise the process and the properties of the finished welded product. Many materials, such as non-alloyed steel, require the use of an active gas to ensure process stability and reliability. Argon/carbon dioxide and argon/oxygen are examples of active gas mixes. Active gases are suited to stainless, high-alloy steels, as well as to unalloyed and low-alloy steels. Three of the most important active gases are CO_2, O_2 and H_2.

- Carbon Dioxide (CO_2) is inert at room temperature. In the presence of the arc plasma and the molten weld puddle it is reactive. In the high energy of the arc plasma the CO_2 molecule breaks apart in a process known as dissociation. Higher levels of carbon dioxide (higher oxidation potential) increases the amount of slag formed on the surface of the weld. Lower levels of carbon dioxide (lower oxidation potential) increase the amount of alloy, silicon and manganese retained in the weld. As a result, lower carbon dioxide levels, in a binary or ternary shielding gas blend, increase the yield and ultimate tensile strength of a finished weld.

- Oxygen (O_2) is an oxidizer that reacts with components in the molten puddle to form oxides. In small additions (1-5%), with a balance of argon, it provides good arc stability and excellent weld bead appearance. The use of deoxidizers within the chemistry of filler alloys compensates for the oxidizing effect of oxygen. Silicon and manganese combine with oxygen to form oxides. The oxides float to the surface of the weld bead to form small islands, and are more abundant under CO_2 shielding than with blends of argon and oxygen gas.

- Hydrogen (H_2) in small percentages (1-5%) is added to argon for shielding stainless steel and nickel alloys. Its higher thermal conductivity

produces a fluid puddle, which promotes improved toe wetting and permits the use of faster travel speeds.

MAG welding, as with all other welding, creates fumes and gases that are dangerous for the welder. This is why safety measures must always be observed. To protect the welder from these fumes, high priority must be given to providing good ventilation in the welding area.

By using an unconventional set of welding parameters, the traditional operational areas for MAG welding can be exceeded and consequently significantly increase productivity.

4.1.2 Laser Welding

Laser-beam welding uses a moving high-density (10^5 to 10^7 W/cm^2) coherent optical energy source called a laser as the source of heat. The ability of the laser to generate a power density greater than 10^6 W/cm^2 is a primary factor in establishing its potential for welding (see figure 4.3).

Laser is an acronym for "light amplification by stimulated emission of radiation." The coherent nature of the laser beam allows it to be focused to a small spot, leading to high energy densities. Lasers have been promoted as potentially useful welding tools for a variety of applications. Until the 1970s, however, laser welding had been restricted to relatively thin materials and low speeds because of the limited continuous power available. By 1965, a variety of laser systems had been developed for making micro welds in electronic circuit boards, inside vacuum tubes, and in other specialized applications where conventional technology was unable to provide reliable joining.

There are several different kinds of laser for different characteristics, but the commonest types of welding lasers are the CO_2 laser and the Nd:YAG laser, attending of the different requirements needed for each kind of process [4] [6].

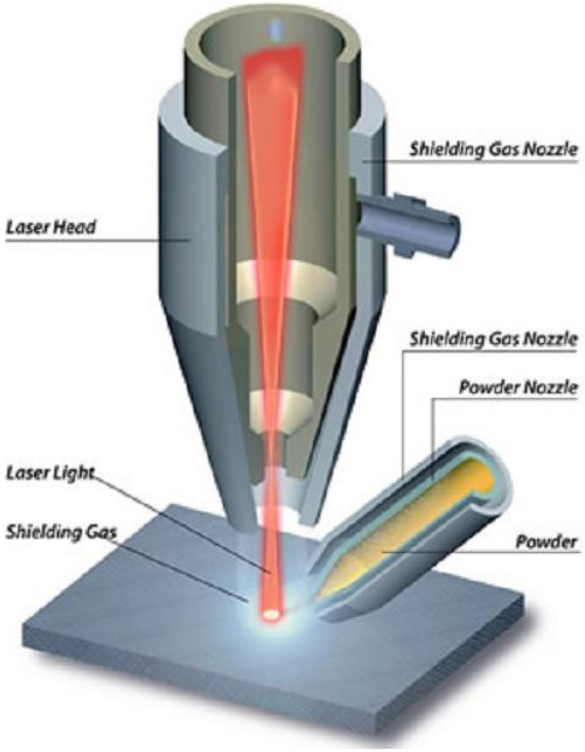

Figure 4.3: Laser Welding diagram [19]

There are two different modes of laser welding: Conduction welding and Penetration (or Keyhole) welding [19] (see figure 4.4).

- In conduction welding, the surface of the weld pool remains unbroken. The materials to be joined are melted by absorption of the laser beam at the material surface from where the heat flows into depth – the solidified melt joins the materials. Welding penetration depths are typically below 2mm.

- In penetration welding, the surface opens up to allow the laser beam to enter the melt pool. At energy densities of approx. 10^6 W/cm^2 evaporation is reached and a vapour capillary is created inside the material. The resulting vapour pressure inside the material keeps the capillary open. Multiple reflections inside the keyhole guide the incident laser beam deep into the material and enhance its absorption.

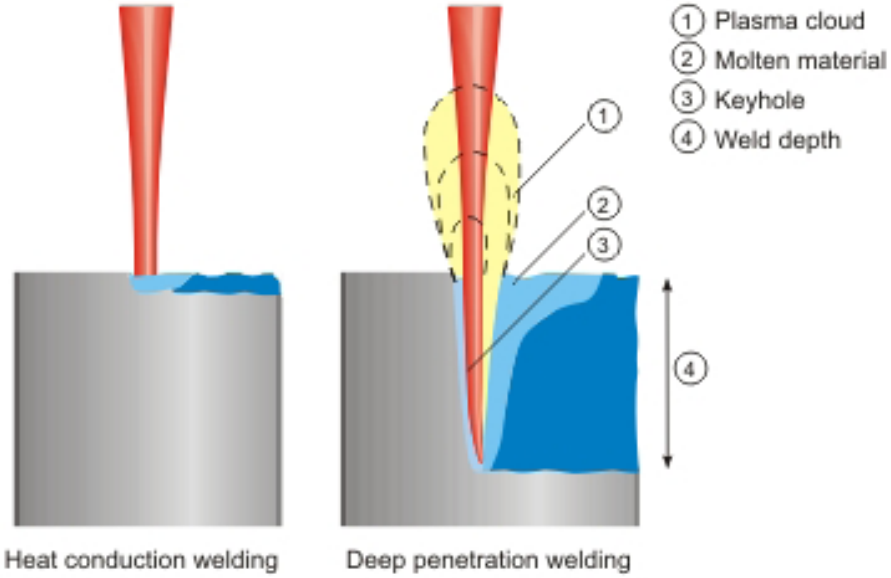

Figure 4.4: Laser Welding [19]

Numerous experiments have shown that the laser permits precision (that is, high quality) weld joints rivalled only by those made with an electron beam [1].

Advantages of Laser welding:

- Focused laser light provides high energy density.
- Precise control of spot intensity (determined by laser power and focus diameter).
- Narrow and deep welds can be made.
- High processes speed.
- The heat affected zone (HAZ) is very narrow.
- Low thermal material influence, low distortion.
- No electrode or filler material are required.
- Precise and high quality welds can be obtained.
- Improves metallurgical and mechanical properties.
- Diverse materials (including some unweldable) and different thicknesses can be joined.
- High flexibility and reliability.
- Easy conversion to automatic operation.

Disadvantages of Laser Welding:

- Poor electrical efficiency (5-10 % for CO_2 lasers, 1-3 % for Nd:YAG lasers).
- Limited welding positions.
- High capital cost.
- Inability to accommodate gaps and mismatch typically found in industry.
- Requires high precision during edge preparation and setup.
- A narrow heat affected zone (HAZ) characterized by high cooling rates that can result in a loss of ductility with certain materials.

4.1.3 Hybrid Laser Welding

Laser hybrid arc welding combines laser and electric arc welding (usually MIG/MAG) and compensates the drawbacks or weaknesses occurring in laser welding and arc welding. It uses the advantages of high precision, welding speed and penetration depth with very low heat input and small heat affected zone (HAZ) associated with lasers and the addition of cheap extra heat input and wire addition (enables gap bridging) (see figure 4.5).

Geometrically, the hybrid process can be arranged either in a combined operation point or separate operate points, where the technique can be parallel or serial. In serial or combined operation points, the working distances between the processes and which process is leading or trailing greatly influences the resulting weld quality [4].

Laser beams and electric arcs are quite different welding heat sources, but both work beneath a shielding gas at ambient pressure, making it possible to combine these heat sources and forming the hybrid process.

The concept of LHAW was introduced in the 1970's by Steen and Eboo when they combined a 2-kW CO_2 laser and a TIG arc in welding and cutting. Investigations showed that combining the laser beam and arc in a common process zone is more than a mere combination of heat sources. Since then, the idea has been developed by many scientists and engineers. Combinations have involved setups with common process zone, arrangements where the processes are working separately and also setups with more than two heat sources. Probably, the most important feature of laser beam heat sources is the precise control of spot intensity (determined by laser power and focus diameter).

Due to improvements in productivity, efficiency and quality, it can be expected that hybrid welding methods will be increasingly adopted for future industrial welding applications.

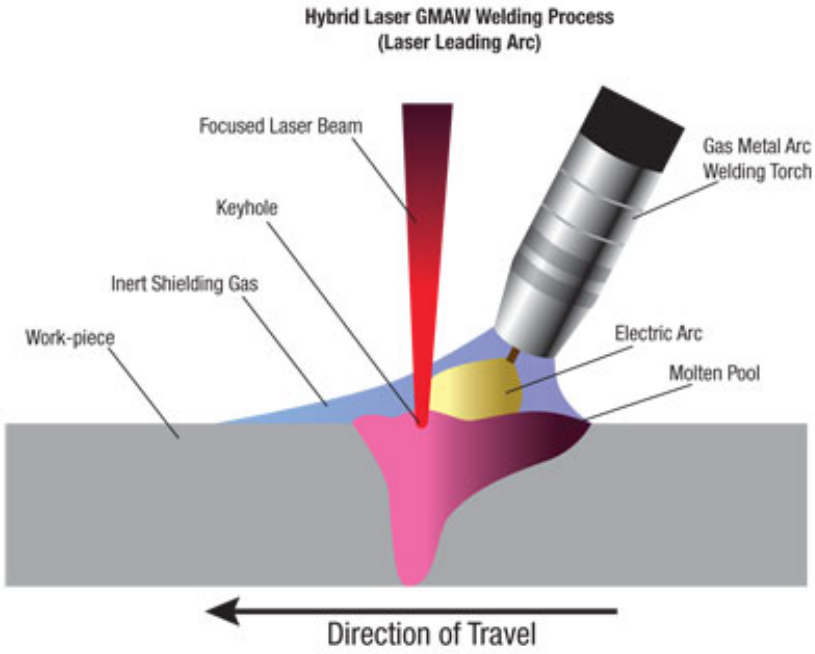

Figure 4.5: Hybrid Laser diagram [19]

Advantages of laser hybrid process:

- Offers good gap bridging capabilities (which are influenced by the heat source separation).
- Increase of weld penetration.
- Higher welding speeds.
- Pore reduction.
- Relatively low heat inputs and high process flexibility.
- Improve the ductility as compared to entirely laser welded parts.
- Easier welding of highly reflective materials.
- Lower capital cost compared to laser alone.
- The addition of filler wire let control of metallurgical variables.
- Reduce overall weld time in thick sections by joining in a single pass.
- Higher electrical efficiency.

Disadvantages of laser hybrid process:

- High number of process parameters that must be adapted for optimal welding results.
- Welding standards and experience widely missing yet.
- Control systematically is more difficult.

4.2 Mechanical Behaviour

4.2.1 Fatigue

Fatigue cracking is one of the primary damage mechanisms of structural components. The occurrence of fatigue can be generally defined as the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material. Fatigue damage is caused by the simultaneous action of cyclic stress, tensile stress, and plastic strain. If any one of these three is not present, a fatigue crack will not initiate and propagate. The plastic strain resulting from cyclic stress initiates the crack; the tensile stress promotes crack growth (propagation).

There are three basic factors necessary to cause fatigue: (1) a maximum tensile stress of sufficiently high value, (2) a large enough variation or fluctuation in the applied stress, and (3) a sufficiently large number of cycles of the applied stress. There are many types of fluctuating stresses. Several of the more common types encountered are shown in figure 4.6 [8].

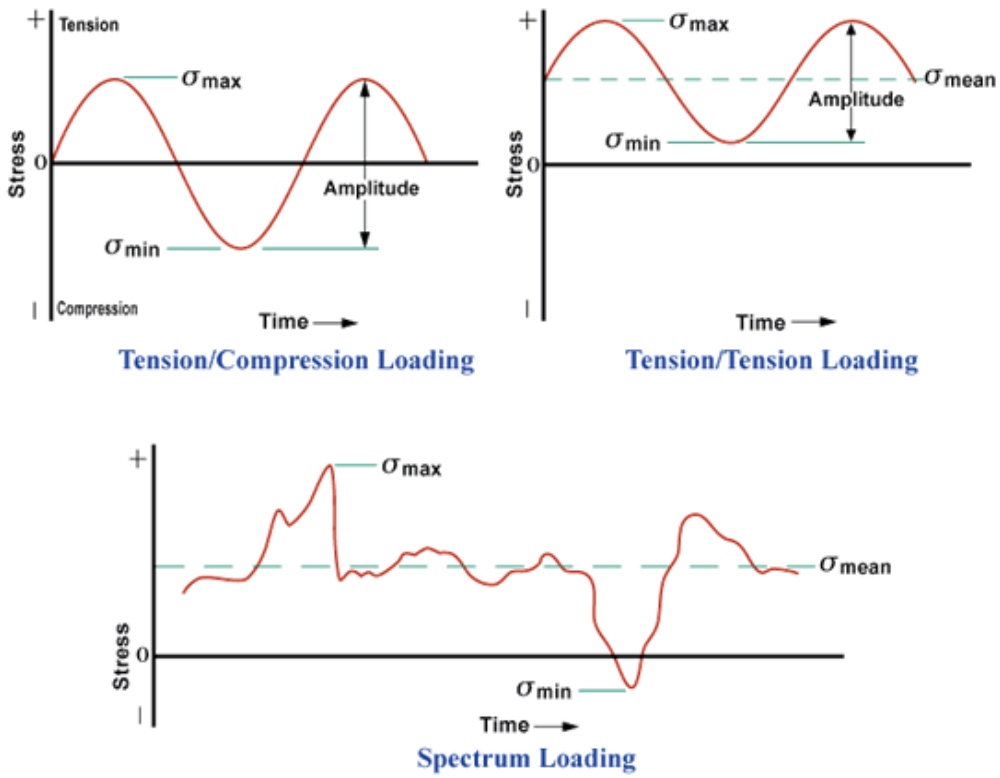

Figure 4.6: Types of fluctuating stresses

The figure shows several types of loading that could initiate a fatigue crack. The upper left figure shows sinusoidal loading going from a tensile stress to a compressive stress. For this type of stress cycle the maximum and minimum stresses are equal. Tensile stress is considered positive, and compressive stress is negative. The figure in the upper right shows sinusoidal loading with the minimum and maximum stresses both in the tensile realm. Cyclic compression loading can also cause fatigue. The lower figure shows variable-amplitude loading, which might be experienced by a bridge or airplane wing or any other component that experiences changing loading patterns. In variable-amplitude loading, only those cycles exceeding some peak threshold will contribute to fatigue cracking.

In addition to these three basic factors, there are a host of other variables, such as stress concentration, corrosion, temperature, overload, metallurgical structure, and residual stresses which can affect the propensity for fatigue. The higher the stress concentration the more likely a crack is to nucleate. Notches, scratches, and other stress risers

decrease fatigue life. Surface residual stress will also have a significant effect on fatigue life. Compressive residual stresses from machining, cold working, heat treating will oppose a tensile load and thus lower the amplitude of cyclic loading.

Fatigue is a problem that can affect any part or component that moves. Automobiles on roads, aircraft wings and fuselages, ships at sea, nuclear reactors, jet engines, and land-based turbines are all subject to fatigue failures. Fatigue was initially recognized as a problem in the early 1800s when investigators in Europe observed that bridge and railroad components were cracking when subjected to repeated loading. As the century progressed and the use of metals expanded with the increasing use of machines, more and more failures of components subjected to repeated loads were recorded. Today, structural fatigue has assumed an even greater importance as a result of the ever-increasing use of high-strength materials and the desire for higher performance from these materials [19].

In general, the description of fatigue strength of structures can be divided into fracture mechanics based (fatigue crack growth behaviour) and S-N based approaches (stress-life behaviour) (see figure 4.7).

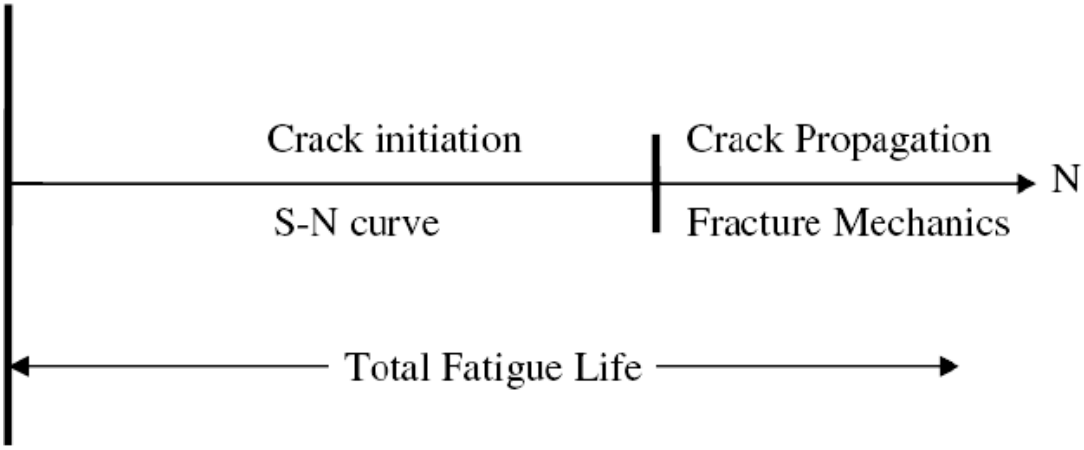

Figure 4.7: Fatigue strength description

The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size. Fatigue cracks almost always initiate at free surfaces, usually external surfaces but also internal surfaces if the metal contains defects such as voids and cracked second-phase particles. Common external surface defects include geometric notches and surface roughness. Fatigue crack nucleation and growth occurs in the following stages. Therefore, it can be said that fatigue failure occurs in three stages – crack initiation; slow, stable crack growth; and rapid fracture (see figure 4.8).

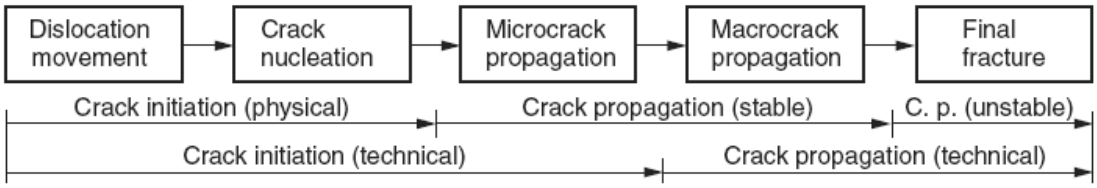

Figure 4.8: Micro- and macro phenomena of material fatigue

In the first stage crack initiation usually starts at a notch or other surface discontinuity. Even in the absence of a surface defect, crack initiation will eventually occur due to the formation of persistent slip bands (PSBs), so called because traces of the bands persist even when the surface damage is polished away. PSBs are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes. This leaves tiny steps in the surface that serve as stress risers where tiny cracks can initiate. These tiny crack (called microcracks) nucleate along planes of high shear stress which is often 45º to the loading direction (see figure 4.9). The crack propagation rate during stage I is very low, on the order of 1 nm per cycle, and produces a practically featureless fracture surface [17].

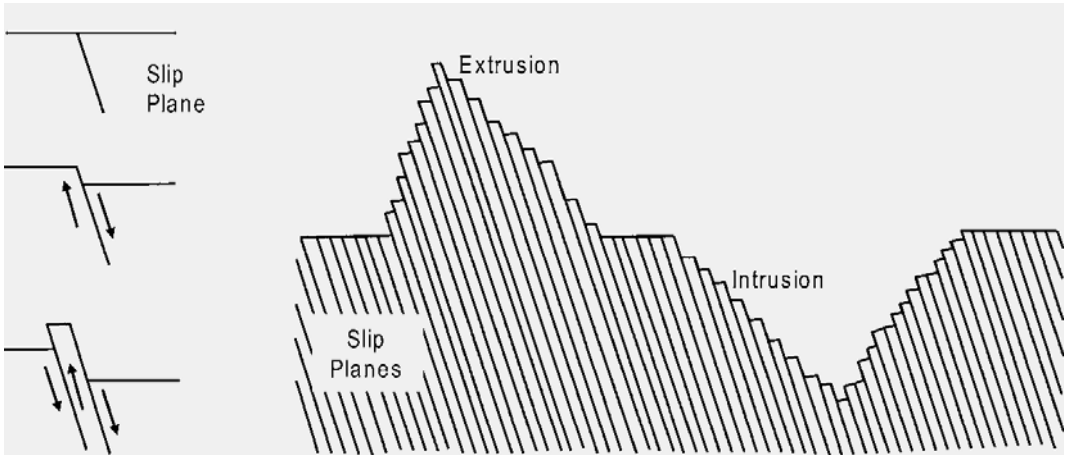

Figure 4.9: Development of extrusions and intrusions during fatigue [19]

In the second stage of fatigue, some of the tiny microcracks join together and begin to propagate through the material in a direction that is perpendicular to the maximum tensile stress. Eventually, the growth of one or a few crack of the larger cracks will dominate over the rest of the cracks. Crack propagation during crack growth often produces a pattern of fatigue striations, with each striation representing one cycle of fatigue. Although striations are indicative of fatigue, fatigue failures can occur without the formation of striations. With continued cyclic loading, the growth of the dominate crack or cracks will continue until the remaining uncracked section of the component can no longer support the load.

Ultimate failure occurs when the fatigue crack becomes long enough that the remaining cross section can no longer support the applied load. At this point, the fracture toughness is exceeded and the remaining cross-section of the material experiences rapid fracture. This rapid overload fracture is the third stage of fatigue failure (see figure 4.10).

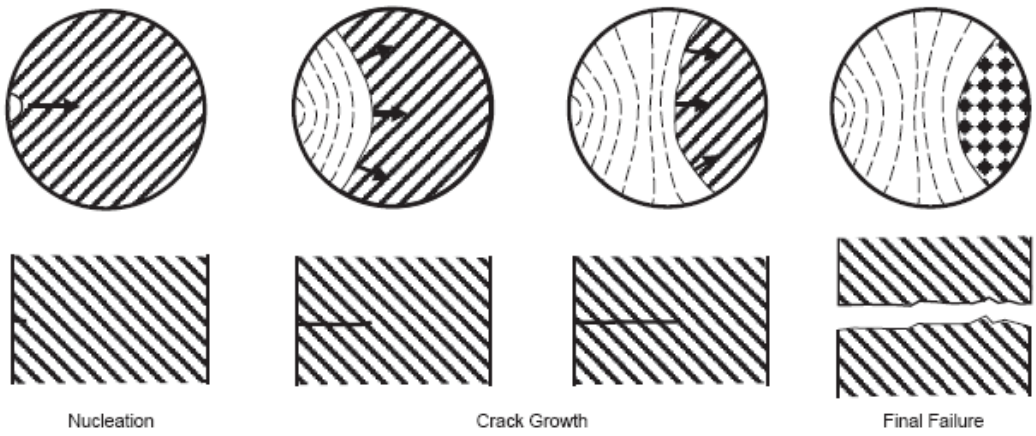

Figure 4.10: Typical propagation of a fatigue crack [19]

In most structures, fatigue cracking usually initiates at a stress concentration. The stress concentration may by inherent in the design, such as a fillet, hole, thread, or other geometrical feature, or the stress concentration can result from a manufacturing process, such as a rough surface finish or residual tensile stresses introduced by heat treatment.

Welding method is a manufacturing process with several stress concentration factors.

- Welding defects and imperfections typical of welded joints are, for example, cracks, pores, cavities, undercuts, lack of fusion, overlap, inadequate penetration and burn through holes.

- Welding residual stress and distortions are another characteristic of welded joints.

Studies of the fatigue resistance of welded joints strongly rely on experiments. This is mainly due to the extremely local phenomenon of the process of fatigue damage. However, the codes for practical fatigue design require information concerning the parameters that affect the fatigue process, derived from theoretical models.

5. Summary of papers

Paper I: Influence of Weld Method on Fatigue Strength. Torsional Fatigue Test

Abstract

A very large percentage of product failures occur at joints because they are usually located at the highest stress points of an assembly and are therefore the weakest parts of that assembly. Different welding processes have different effects on the fatigue properties of welded joints.

In this paper, a comparison of the influence of MAG and Hybrid-Laser welding method on fatigue strength of an automotive piece is carried out. For that, several torsional fatigue tests were realized in Gestamp Laboratory in Luleå.

Conclusions

- The torsional fatigue tests confirm that Hybrid Laser welding method is better than MAG welding method on fatigue behaviour.

  - In MAG welded pieces, the fracture occurs in the weld. The fatigue life depends on the load amplitude.
  - In Hybrid Laser welded pieces, the fracture occurs in the base material.

- If the welding method is changed to one that produces fewer defects, the fatigue behaviour will be better. Hybrid welding joints show a pore reduction and an elimination of cracks and the ability to produce desirable weld profiles resulted in fatigue life superior to that of conventional welds.

Paper II: Reengineering analysis: Thickness reduction in hybrid laser welding case

Abstract

The torsional fatigue test has demonstrated that Hybrid Laser welding has higher fatigue strength. Therefore, a thickness reduction that guarantees a similar structural integrity to MAG welded workpieces is possible to optimize the material cost.

In this paper, the thickness reduction and cost is calculated. This cost is separated in four parts: Raw material, Cutting material, Bending material and Welding material.

Conclusions

- Changing welding method to Hybrid Laser let a thickness reduction around 65%.

- The total cost reduction is 54´65%.

6. General conclusions of the thesis

From the papers in this thesis, the following general conclusions can be drawn:

- Hybrid welding shows a pore reduction and an elimination of cracks. The ability of the laser-welding process to produce desirable weld profiles resulted in fatigue life superior to that of conventional welds.

- The torsional fatigue tests confirm that Hybrid Laser welding method is better than MAG welding method on fatigue behaviour. In MAG welded pieces, the fracture occurs in the weld. The fatigue life depends on the load amplitude. In Hybrid Laser welded pieces, the fracture occurs in the base material.

- Changing welding method to Hybrid Laser let a thickness reduction around 65%. The total cost reduction is 54´65%.

7. Future outlook

Although the here presented thesis has described and discussed the knowledge in the welding community (in particular addressing the fatigue behaviour) further development of documentation is needed.

Nowadays, laser and hybrid laser welding are advanced welding technologies for which numerous researches have already been carried out. Still research on stress analysis of laser welded joint is unsatisfactory. More and more complex welded products are invented by the designers, including the use of high strength metals, which requires proper investigation to achieve the desired mechanical strength.

In this thesis, the thickness of one automotive workpiece has been modified. For validation this thickness reduction it would be necessary to make several mechanical tests like:

- Fatigue behaviour
- Torsional

It is possible that the new welding method selected (hybrid laser) could be optimized, hence it would be interesting analyze different hybrid-laser welding parameters to improve mechanical properties of the workpiece.

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PAPER I

Influence of Weld Method on Fatigue Strength. Torsional Fatigue Test

Abstract

A very large percentage of product failures occur at joints because they are usually located at the highest stress points of an assembly and are therefore the weakest parts of that assembly. Different welding processes have different effects on the fatigue properties of welded joints.

Mechanical testing machines have been commercially available since 1886 and have evolved from purely mechanical machines to more sophisticate electromechanical and servo hydraulic machines with advanced electronics and microcomputers.

In this paper, a comparison of the influence of MAG and Hybrid-Laser welding method on fatigue strength of an automotive piece is carried out. For that, several torsional fatigue tests were realized in Gestamp Laboratory in Luleå.

Keywords: testing machine, fatigue behaviour, Laser Hybrid, MAG, torsional test.

1. Introduction

A very large percentage of product failures occur at joints because they are usually located at the highest stress points of an assembly and are therefore the weakest parts of that assembly. Careful attention to the joining processes can produce great rewards in manufacturing economy and product reliability.

Welding is generally performed by melting the surfaces of the parts to be joined, together with the filler material, using a concentrated heat source. The subsequent rapid cooling produces residual stresses and distortions via thermal strains and microstructural transformation. These welding residual stresses may reach the yield limit in the weld area and decrease sharply in its neighbourhood. They have a generally low level outside the weld area, but produce local stress concentrations at notches. Residual stresses in weldments have two effects. Firstly, they produce distortion, and second, they can be the cause of premature failure especially in fatigue fracture under lower external cyclic loads [2].

Many distinct factors influence the strength of welds and the material around them, including the welding method, the amount and concentration of energy input, the weldability of the base material, filler material, and flux material, the design of the joint, and the interactions between all these factors. All these factors influence the residual stress, weld bead geometry and the presence of welding defects like cracks, distortion, gas inclusions (porosity), non-metallic inclusions, lack of fusion, incomplete penetration, lamellar tearing, and undercutting [6] (see figure 1).

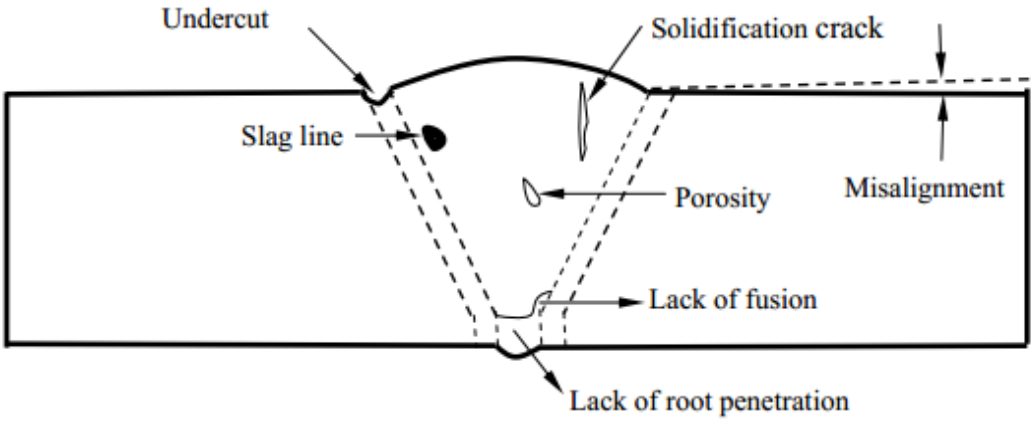

Figure 1: Welding defects

Different welding processes have different effects on the fatigue properties of welded joints. Two of the most prevalent quality problems in GMAW are dross and porosity. Laser welding presents occasional

metallurgical problems due to the high cooling rates. Hybrid welding increases liquid melt volume, resulting in less sensitivity to welding defects and hence hybrid welding joints show a pore reduction and an elimination of cracks [4].

If the welding method is changed to one that produces fewer defects, the fatigue behaviour will be better. For example, Lack of Fusion slightly (<10%) reduces the fatigue life by accelerating the crack propagation [1]. When a crack propagates closer to LOF, the interaction increases the stress around the crack and accelerates it, slightly (< 10%) reducing the fatigue life for the here studied case. As mentioned in previous sections, Hybrid-laser welding method reduces this defect significantly compared with MAG method.

Early researches have generally established that the fatigue life comprises of two phases: crack initiation and crack propagation. In smooth specimens the crack initiation phase comprises of a considerable proportion of the total life. In welded steel structures, fatigue cracks will almost certainly start to grow from welds, rather than other details, because most welding processes leave minute metallurgical discontinuities from which cracks may grow. These crack-like defects begin to grow almost immediately when subjected to external cyclic fatigue loads. As a result, the initiation period, which is normally needed to start a crack in plain wrought material, is either very short or no-existent. Cracks therefore spend most of their life propagating, i.e. getting longer, so that, for welded joints, the total fatigue life is mainly dominated by the crack propagation phase. It has been known that fatigue crack growth behaviours of welded joints are highly dependent not only on the materials and load conditions but also on weld geometry such as weld toe angle, weld toe root radius, plate thickness, width of the weld reinforcement and height of reinforcement [5].

To test the quality of a weld, either destructive or non-destructive testing methods are commonly used to verify that welds are free of defects,

have acceptable levels of residual stresses and distortion, and have acceptable heat-affected zone (HAZ) properties. Methods such as visual inspection, radiography, ultrasonic testing, dye penetrant inspection, Magnetic-particle inspection or industrial CT scanning can help with detection and analysis of certain defects.

Most fatigue testing machines have been developed to a high degree and are marketed commercially to laboratories for conducting a wide variety of fatigue testing. Machines have been developed for various modes of loading that, in turn, dictate the configuration of the test specimen. Three basic modes of loading are used: direct axial loading, plane-bending, and rotating-beam loading.

In addition to the loading mode, fatigue testing machines are further classified by their basic drive mechanism and by the test parameter to be controlled. The basic drive system is most often electrical. An electric motor directly drives rotating-beam testing machines. All fatigue testing machines have a basic loading frame that resists the loads imposed on the test specimen. This frame also supports a number of other components, including the drive mechanism that transmits loading to the specimen through grips, load cells, extensometer, and other measurement devices. The testing machine should undergo as little elastic loading displacement as possible. Ideally, the bulk of the displacement should be absorbed by the specimen. The loading train within the testing machine should also have excellent alignment of the load line with the specimen to prevent premature specimen warping or buckling under high loads.

Rotating-beam machines are the earliest type of fatigue testing machine, and they remain in occasional use today. The specimen has a round cross section and is subjected to dead-weight loading while swivel bearings permit rotation. A given point on the circular test-section surface, during each rotation, is subjected to sinusoidal stress variation from tension on the top to compression on the bottom. The simpler

fatigue testing machines based on constant loading or displacement in plane bending, rotating bending, and direct stress are used almost exclusively for evaluation of very-high-cycle fatigue resistance of materials [3].

2. Experimental Work

To check the influence of welding method on fatigue strength, several samples of a beam member welded by MAG and by Hybrid-Laser method were tested in the laboratories of a company in Luleå.

A brief description about the test machine used is presented below [6] (see figure 2).

Servo-Hydraulic Load Frame - HB Series

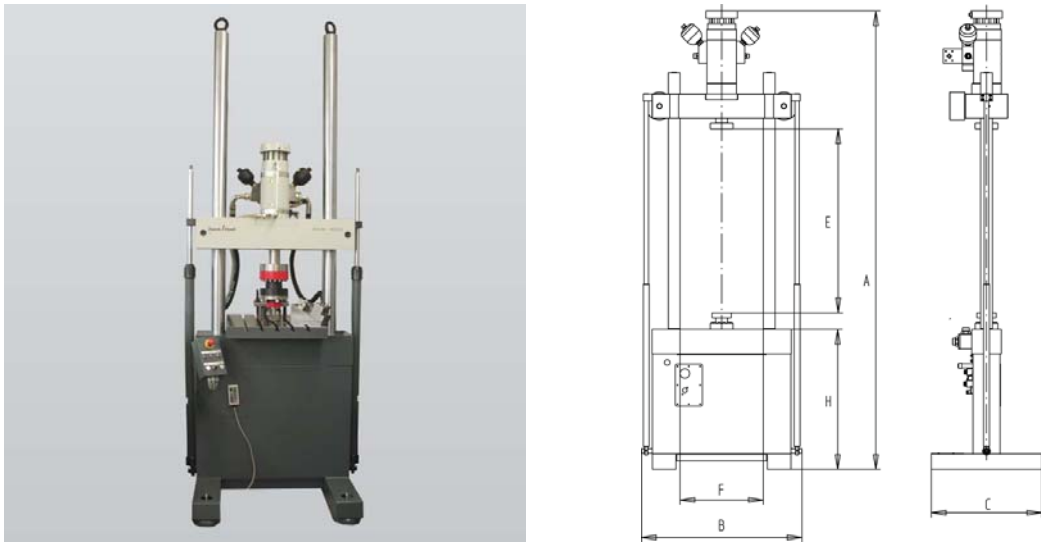

Figure 2: Servo-Hydraulic Load Frame - HB Series [6]

Applications

Single actuator loading frame for testing materials and components.

Advantages

• Wide range of options and flexibility in design to meet specific needs.

• No special foundations are required.

• Ease of access with only two columns.

• Reliable and fully fatigue rated at the specified force

• Accuracy and repeatability – The Amsler frames have an excellent reputation resulting from precision engineering and high stiffness.

• Wide range of static and dynamic tooling.

• Customized or special tooling manufactured.

• Movable or fixed crosshead.

Features and Benefits

• Alignment is maintained over the height of the frame by using precision machined columns.

• Long life and easy cleaning of the columns by construction with solid steel and chrome plating.

• Accurate displacement measurement by using high stiffness crossheads and coaxially mounted displacement transducers.

• Good displacement measurement by using high stiffness crossheads and coaxially mounted displacement measurement transducers.

• Flexibility. The top mounted actuator provides for easy mounting and assembly of components and non regular test pieces. Different capacity actuators can be accommodated into the frame.

• Versatility. Testing from only a few Hz to 200 Hz and from mm/min to m/s.

• Safety. Frames are CE compliant when fitted with a safety shield.

• Various options for frames. Many options are available, e.g. vibration isolation, extended heights and widths, guards, T-slotted tables and higher capacity frames.

• Numerous options for actuators. e.g. linear and/or torsion drives, different force capacities, stroke lengths, operating pressure, number and type of servo valves and anti rotation devices.

Product codes

Dynamic Force Capacity (kN)	Upper crosshead lifting and locking options		
	Manual Lift and Manual Lock	Hydraulic Lift and Manual Lock	Hydraulic Lift and Hydraulic Lock
50	BPS-FB0050.00.xx	BPS-FB0050.10.xx	BPS-FB0050.20.xx
100	BPS-FB0100.00.xx	BPS-FB0100.10.xx	BPS-FB0100.20.xx
250	BPS-FB0250.00.xx	BPS-FB0250.10.xx	BPS-FB0250.20.xx
500	BPS-FB0500.00.xx	BPS-FB0500.10.xx	BPS-FB0500.20.xx

Figure 3: Product codes

Actuator options

• Linear or rotary actuators or combined linear/rotary drives.

• Frames can be used with actuators of different capacities.

• Anti Rotation Devices.

• Standard actuator stroke length 100 mm or 250 mm; other lengths on request.

• Supplied as standard with plain bearing actuators – optionally hydrostatic bearings are available.

• System pressure 210 bar or 280 bar.

• For servo valve combinations (e.g. twin servo manifolds and/or high flow valves) please discuss with Zwick engineers to calculate system performance.

Dimensions of standard frames

			FB0050	FB0100	FB0250	FB0500
A	Overall Height	[mm]	2825 + 2x actuator stoke	2825 + 2x actuator stoke	3530 + 2x actuator stoke	3880 + 2x actuator stoke
B	Machine Width	[mm]	1075	1075	1200	1440
C	Machine Depth	[mm]	750	750	1100	1310
E	Vertical test space	[mm]	100...1100	100...1100	100...1500	100...1500
F	Horizontal test space	[mm]	565	565	670	800
G	Height of bottom crosshead	[mm]	960	960	1100	1150
H	Height of bottom tool mounting face	[mm]	1110	1110	1320	1470
I	Height to top of column	[mm]	2710	2710	3360	4350
P	Hydraulic pressure input		¾" BSP	¾" BSP	¾" BSP	¾" BSP
R	Hydraulic return output		¼" BSP	¼" BSP	¼" BSP	¼" BSP
D	Hydraulic drain connection		1" BSP	1" BSP	1" BSP	1" BSP
	Alignment eccentricity					
	0 … 350 mm	[mm]	0.05	0.05	0.05	0.05
	above 350 mm	[mm/m]	+ 0.1	+ 0.1	+ 0.1	+ 0.1
	Parallelism per 100 mm	[mm]	0.03	0.03	0.03	0.03
	Stiffness at 1000 mm crosshead separation	[kN/mm]	850	850	1600	2300
	Net weight	[kg]	1030	1030	1500	2450

Note: These specifications are nominal. The inclusion of options may vary these specifications.

Figure 4: Dimensions of standard frames

3. Results and Discussion

Here, the results from the torsional fatigue test are presented.

- **MAG welding method.**

The results of the torsional fatigue test of 5 pieces are showed below including their graphics (Stroke vs. Cycles) and a picture of the workpiece tested.

In this first test, the piece BO-MAG 4-1 was submitted to a 6´5 kN load. As you can see in the figure 5, the stroke increased after 20 cycles and the piece broke up before 60 cycles due to the high cyclic load.

Test BO-MAG 4-1

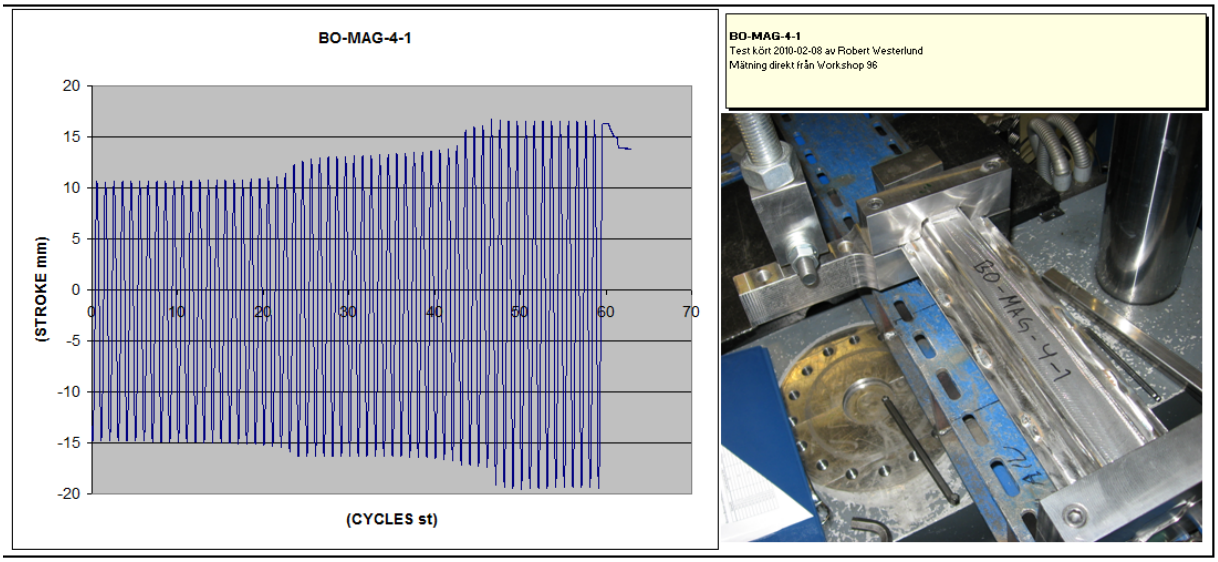

Figure 5: BO-MAG 4-1

In the second test, the piece BO-MAG 6-1 was submitted to a 5´2 kN load. As you can see in the figure 6, the stroke increased after 62 cycles and the piece broke up around 390 cycles due to the high cyclic load.

Test BO-MAG 6-1

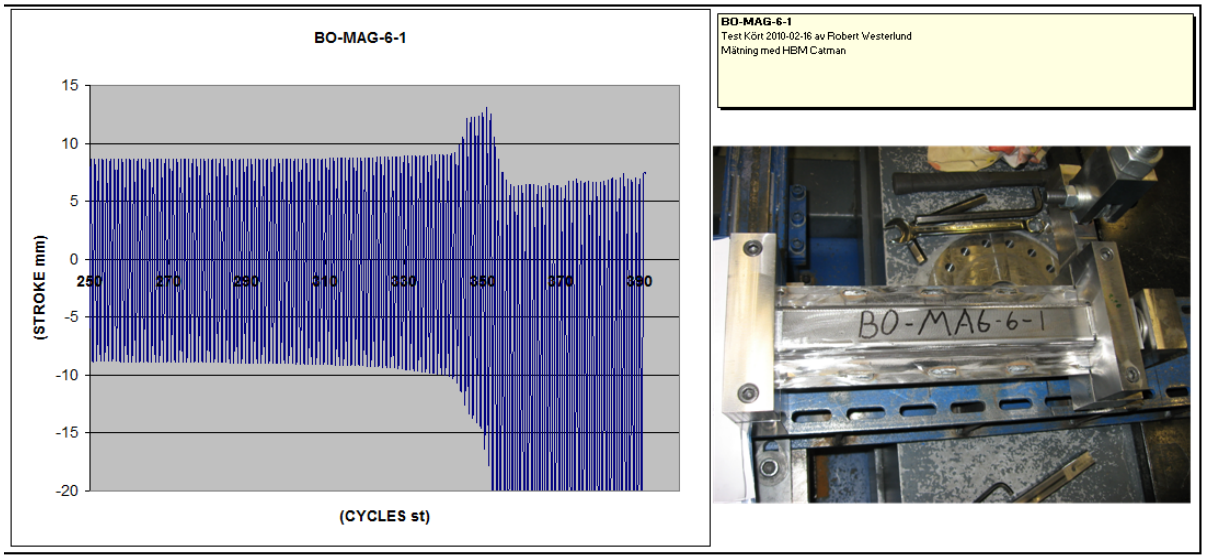

Figure 6: BO-MAG 6-1

In this third test, the piece BO-MAG 6-2 was also submitted to a 5´2 kN load. As you can see in the figure 7, the stroke increased after 111 cycles and the piece broke up after 160 cycles due to the high cyclic load.

Test BO-MAG 6-2

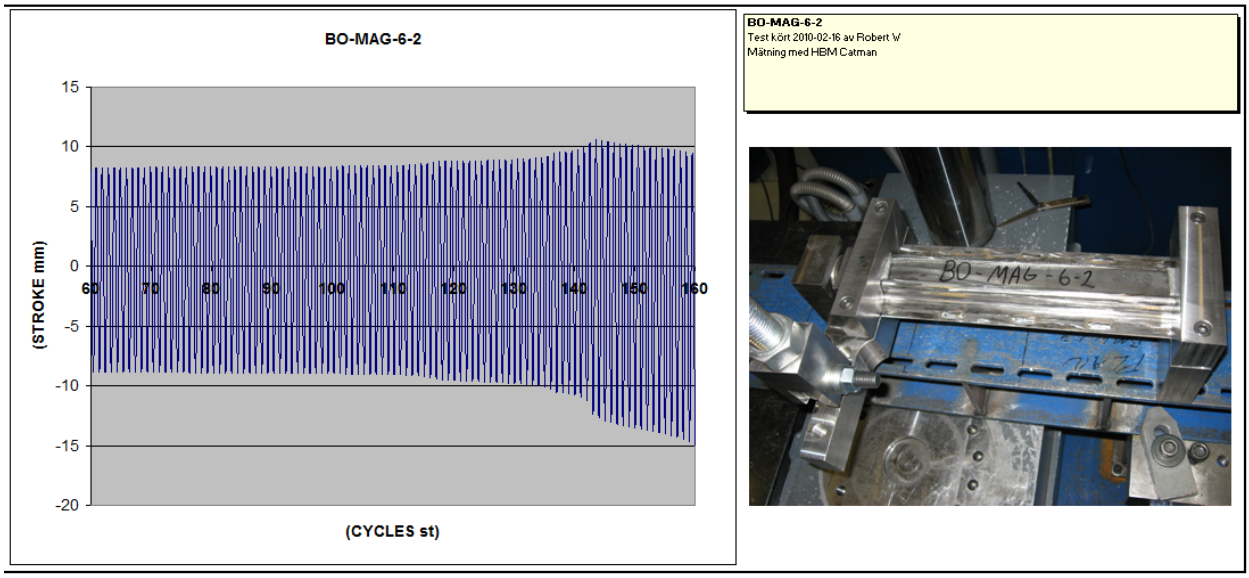

Figure 7: BO-MAG 6-2

In this fourth test, the piece BO-MAG 6-3 was also submitted to a 5´2 kN load. As you can see in the figure 8, the stroke increased after 60 cycles and the piece broke up around 74 cycles due to the high cyclic load.

Test BO-MAG 6-3

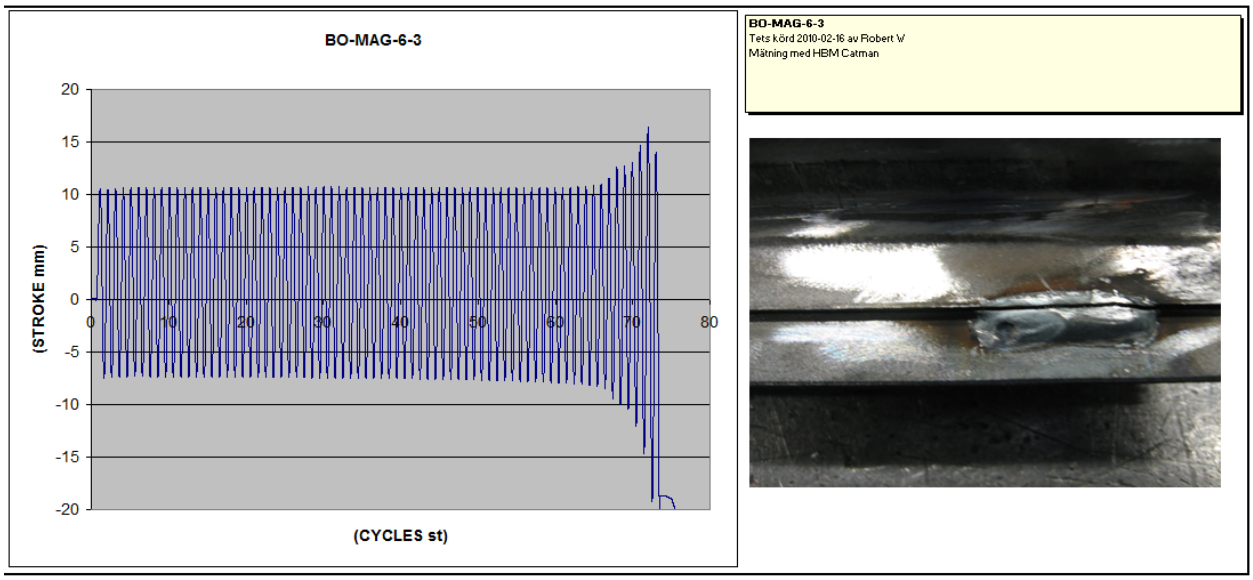

Figure 8: BO-MAG 6-3

In this fifth test, the piece BO-MAG 7-1 was submitted to a 3´9 kN load. As you can see in the figure 9, the stroke increased after 406 cycles and the piece broke up around 710 cycles due to the cyclic load.

Test BO-MAG 7-1

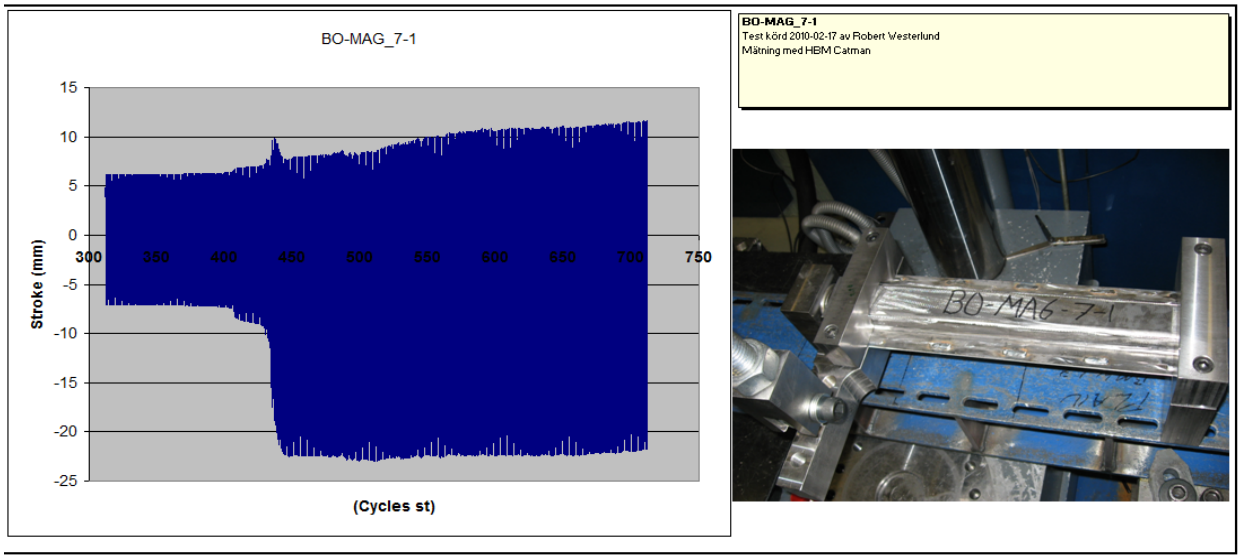

Figure 9: BO-MAG 7-1

Next table (table 1) shows a resume of the results obtained in the tests.

Name	Nº Cycles	Load Amplitude (kN)
4-1	20	6,5
6-1	62	5,2
6-2	111	5,2
6-3	60	5,2
7-1	406	3,9
8-1	18800	2,6
9-1	12000	3,25
9-2	2000	3,25

Table 1: Resume of the results

Finally, this is the S-N curve of the torsional fatigue test obtained:

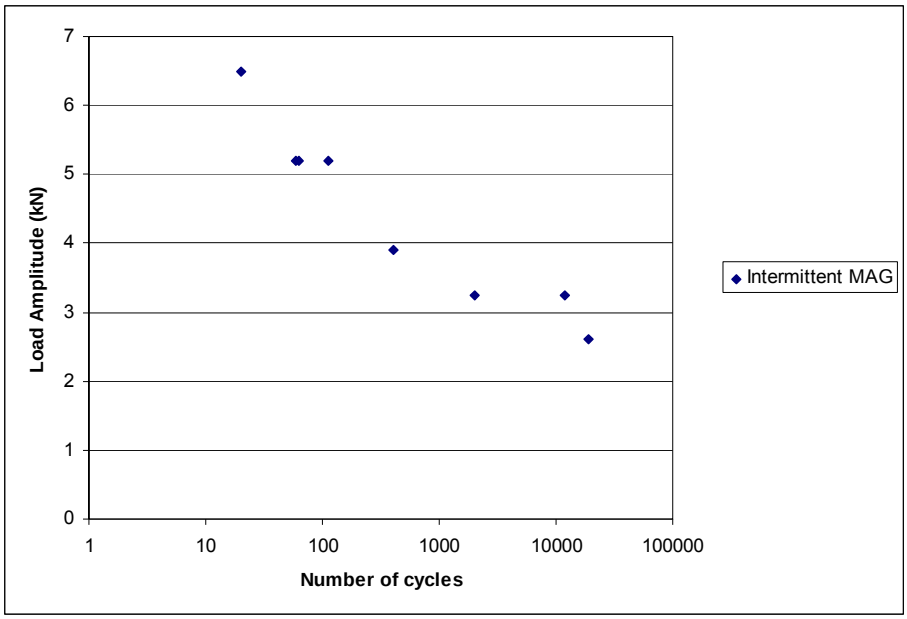

Figure 10: S-N curve

This graphic shows the relation between the value of load amplitude and the number of cycles required to produce failure in the test piece. Greater load amplitude applied to the piece involves lower number of cycles supported.

- **Hybrid Laser method.**

Only two workpieces were tested because the fracture always occurred in the base material, without any damage in the welded.

Test BO-LH 1-1

This is a picture of the piece BO-LH 1-1 in the machine test (figure 11). The piece BO-LH 1-1 was submitted to a 25 kN load.

Figure 11: BO-LH 1-1

And now, two figures of the failure were presented. As you can in the figures 12 and 13, the fracture occurred in the base material, without any damage in the welded.

Figure 12: BO-LH 1-1

Figure 13: BO-LH 1-1

Test BO-LH 1-2

This is a picture of the piece BO-LH 1-2 in the machine test (figure 14). The piece BO-LH 1-1 was submitted to a 25 kN load.

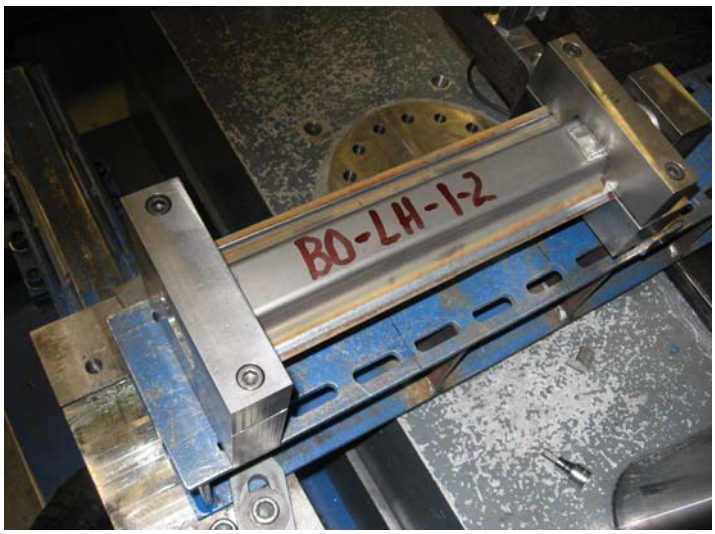

Figure 14: BO-LH 1-2

Next two pictures evince the failure in the piece. As you can in the figures 15 and 16, the fracture also occurred in the base material, without any damage in the welded.

Figure 15: BO-LH 1-2

Figure 16: BO-LH 1-2

Hence, the torsional fatigue tests prove that Hybrid Laser welding has better fatigue strength than MAG welding.

4. Conclusions

- The torsional fatigue tests confirm that Hybrid Laser welding method is better than MAG welding method on fatigue behaviour.

  - In MAG welded pieces, the fracture occurs in the weld. The fatigue life depends on the load amplitude.
  - In Hybrid Laser welded pieces, the fracture occurs in the base material.

- If the welding method is changed to one that produces fewer defects, the fatigue behaviour will be better. Hybrid welding joints show a pore reduction and an elimination of cracks and the ability to produce desirable weld profiles resulted in fatigue life superior to that of conventional welds.

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PAPER II

Reengineering analysis: Thickness reduction in hybrid laser welding case

Abstract

The torsional fatigue test has demonstrated that Hybrid Laser welding has higher fatigue strength. Therefore, a thickness reduction that guarantees a similar structural integrity to MAG welded workpieces is possible to optimize the material cost.

In this paper, the reduction thickness and cost is calculated. This cost is separated in four parts: Raw material, Cutting material, Bending material and Welding material.

Keywords: Thickness reduction, Laser Hybrid, MAG, strength, analysis, cost.

1. Introduction

The ability of the laser-welding process to produce desirable weld profiles resulted in fatigue life superior to that of conventional welds. The laser welded joint geometry (width, penetration depth, melted area) is mainly dependent on the parameters welding speed, laser power, focal plane position shielding gas type/flow and the joint gap [3].

The fatigue strength of welded joints in terms of nominal or structural stress depends on the plate thickness. It has been found that specimens with larger thicknesses, where specimens have the same geometry and loading and the same geometric stress range but a different size, have lower fatigue strength. The reason for this is attributed to the following:

- Geometrical effects: although the geometry might be the same, the stress gradient at the notch is less steep for larger thicknesses. As a result the stresses at the crack tip are larger, thus increasing the crack growth. The geometry is not completely scaled, e.g. the radius of the weld toe is not increased as much as the wall thickness, resulting in a larger thickness effect.
- Statistical effects: statistically, in a larger volume, the probability of a larger defect increases and the fatigue strength decreases with increasing defect size.
- Technological effects: in larger thicknesses, the grain size is coarser, the yield strength is lower, the residual stresses are higher, the toughness is lower and the probability of hydrogen cracking increases, all resulting in lower fatigue strength for thicker specimens [4].

2. Results and Discussion

2.1 Thickness reduction calculation

The torsional fatigue test has demonstrated that Hybrid Laser welding has higher fatigue strength. Therefore, a thickness reduction that guarantees a similar structural integrity to MAG welded workpieces has been calculated to optimize the material cost.

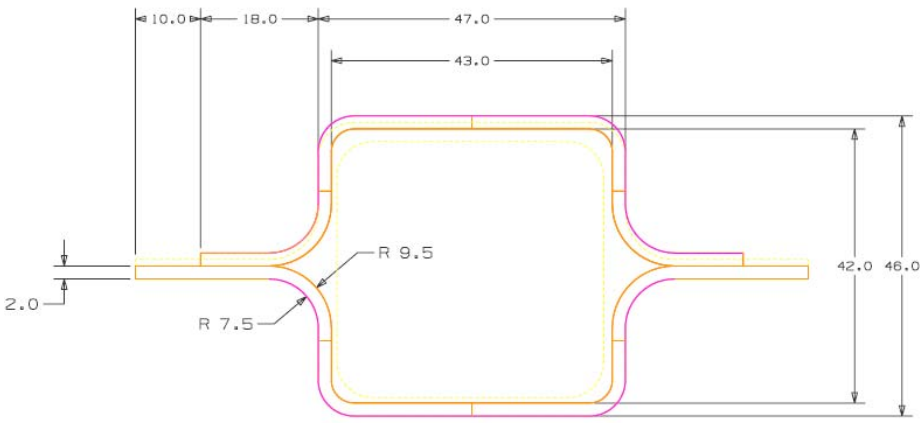

Figure 1: Workpiece cross section

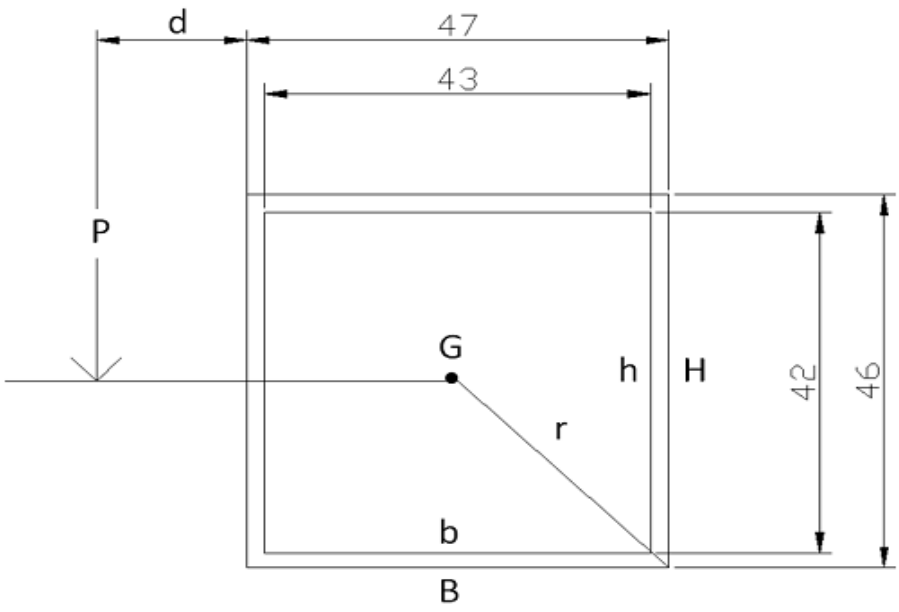

Figure 2: Simplified model of the part

P = Load

G = Centre of Gravity

e = Thickness

M_t = Torque

τ = Torsion Moment

B = 47 mm

b = 43 mm

H = 46 mm

h = 42 mm

$d = \left(\frac{10+18}{2}\right)$ = 14 mm

$r = \sqrt{\left(\frac{46}{2}\right)^2 + \left(\frac{47}{2}\right)^2}$ = 32´88 mm

$I_x = \frac{1}{12} \times B \times H^3$

$I_y = \frac{1}{12} \times H \times B^3$

First of all, the effort supported by MAG welded and Hybrid Laser welded pieces has been calculated with original thickness (2mm).

• MAG Welding

$I_{o1} = I_x + I_y = \frac{1}{12} \times B \times H^3 + \frac{1}{12} \times H \times B^3$

$I_{o2} = I_x + I_y = \left(\frac{1}{12}\right) \times b \times h^3 + \left(\frac{1}{12}\right) \times h \times b^3$

$I_o = I_{o1} - I_{o2} = 235.464´34\ mm^4$

$P_{MAG} = 13.000\ N$

e = 2 mm = Original Thickness

$M_t = \left(\frac{47}{2} + d\right) \times P = \left(\frac{47}{2} + \left(\frac{10+18}{2}\right)\right) \times P$ = 37´5 x 13.000 = 487´5 Nm

$\tau = \frac{Mt \times r}{Io}$ = 68´08 Mpa

• Laser Hybrid Welding

$I_{o1} = I_x + I_y = \frac{1}{12} \times B \times H^3 + \frac{1}{12} \times H \times B^3$

$I_{o2} = I_x + I_y = \left(\frac{1}{12}\right) \times b \times h^3 + \left(\frac{1}{12}\right) \times h \times b^3$

$I_o = I_{o1} - I_{o2} = 235.464´34\ mm^4$

$P_{Hybrid} = 35.000\ N$

e = 2 mm = Original Thickness

$M_t = \left(\frac{47}{2} + d\right) \times P = \left(\frac{47}{2} + \left(\frac{10+18}{2}\right)\right) \times P$ = 37´5 x 35.000 = 1312´5 Nm

$\tau = \frac{Mt \times r}{Io}$ = 183´28 Mpa

Minimum thickness that guarantee an optimum structural integrity:

Once the efforts were obtained, the new thickness was calculated. For that, it is necessary the workpiece support $M_{tHybrid}$ and τ_{MAG}.

τ_{MAG} = 68´08 MPa

$M_{tHybrid}$ = 1312´5 Nm

$$r = \sqrt{\left(\frac{46}{2}\right)^2 + \left(\frac{47}{2}\right)^2} = 32´88 \text{ mm}$$

$$\tau = \frac{Mt \times r}{Io} \Rightarrow I_o = \frac{Mt \times r}{\tau}$$

$$I_o = \left[\frac{1}{6} \times e \times (B+H)^3 - e^2 \times (B+H)^2 + \frac{8}{3} \times e^3 \times (B+H) - \frac{8}{3} \times e^4\right]$$

$$2´67 \times e^4 - 248 \times e^3 + 8649 \times e^2 - 134059´5 \times e + 6´339 \times 10^{-5} = 0$$

e = 0´6818 mm

Hence, the % thickness reduction will be:

$$\% \text{ Thickness reduction} = \left(\frac{2 - 0´6818}{2}\right) \times 100 = 65´91\%$$

%Thickness Reduction = 65´91%

2.2 Cost Calculation

The new thickness calculated induces a cost reduction. This cost is separated in four parts: Raw material, Cutting material, Bending material and Welding material [2].

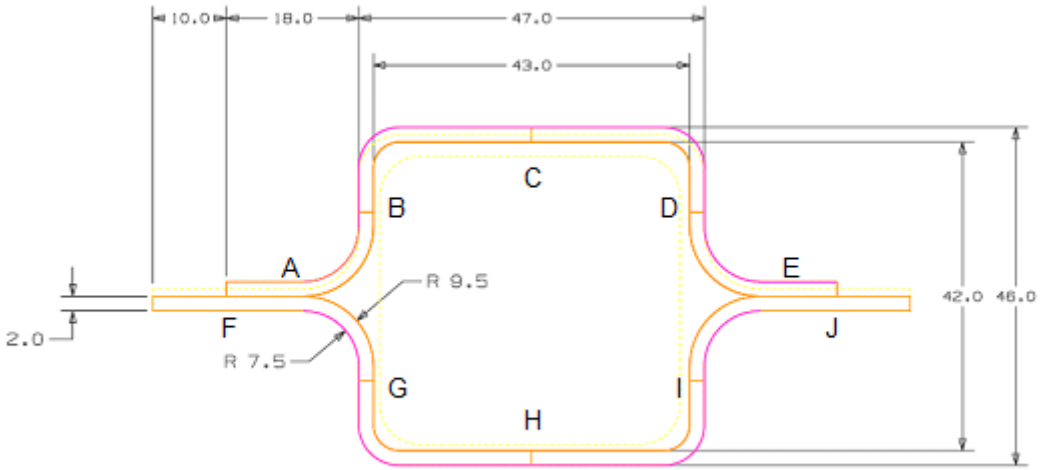

Figure 3: Workpiece cross section

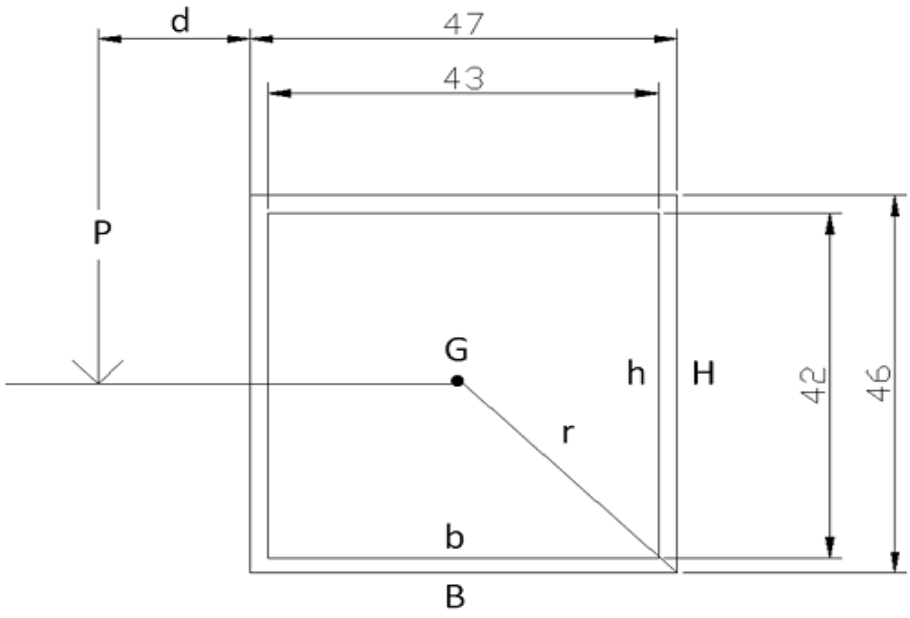

Figure 4: Simplified model of the part

Material: Boron Steel

	Boron Steel 2 mm (MAG)	Boron Steel 0´68 mm (H-L)
Thickness mm	**2´00**	**0´68**
Width mm	**270´00**	**270´00**
Length mm	**500´00**	**500´00**

Table 1: Dimensions

Properties	Carbon Steels	Alloy Steels	Stainless Steels	Tool Steels
Density (1000 kg/m^3)	7.85	7.85	7.75-8.1	7.72-8.0
Elastic Modulus (GPa)	190-210	190-210	190-210	190-210
Poisson's Ratio	0.27-0.3	0.27-0.3	0.27-0.3	0.27-0.3
Thermal Expansion (10^{-6}/K)	11-16.6	9.0-15	9.0-20.7	9.4-15.1
Melting Point (°C)			1371-1454	
Thermal Conductivity (W/m-K)	24.3-65.2	26-48.6	11.2-36.7	19.9-48.3
Specific Heat (J/kg-K)	450-2081	452-1499	420-500	
Electrical Resistivity ($10^{-9}\Omega$-m)	130-1250	210-1251	75.7-1020	
Tensile Strength (MPa)	276-1882	758-1882	515-827	640-2000
Yield Strength (MPa)	186-758	366-1793	207-552	380-440
Percent Elongation (%)	10-32	4-31	12-40	5-25
Hardness (Brinell 3000kg)	86-388	149-627	137-595	210-620

Figure 5: Properties of materials

Approximate Width

Small Sheet (up):

$L_1 = A + B + C + D + E = 18 + 23 + 43 + 23 + 18 = 125$ mm

Large Sheet (down):

$L2 = F + G + H + I + J = 28 + 23 + 43 + 23 + 28 = 145$ mm

Width = $L_1 + L_2 = 125 + 145 = 270$ mm

- **Raw material Cost**

To obtain this, it is necessary to get the weight of both pieces.

Weight = density × volume

Density = 7850 kg/m³

Weight_{MAG} = 7850 kg/m³ × $\left(500mm \times 270mm \times 2mm\right) \times \frac{1m^3}{1000^3 mm^3}$

Weight_{MAG} = 2´12 kg/part

Weight_{Hybrid} = 7850 kg/m³ × $\left(500mm \times 270mm \times 0´68mm\right) \times \frac{1m^3}{1000^3 mm^3}$

Weight_{Hybrid} = 0´72 kg/part

Price = 900 €/t = 0´9 €/kg

Cost_{MAG} = 2´12 kg/part × 0´9 €/kg = 1´91 €/part

Cost_{Hybrid} = 0´72 kg/part × 0´9 €/kg = 0´65 €/part

%Reduction Weight = $\left(\frac{2´12 - 0´72}{2´12}\right) \times 100$ = 66´04 %

%Weight Reduction = 66´04 **%**

%Reduction Cost = $\left(\frac{1´91 - 0´65}{1´91}\right) \times 100$ = 65´97 %

%Raw Material Cost Reduction = 65´97 **%**

- **Laser cutting cost**

Here, an analysis of laser cutting cost to get the desired sheet is realized.

MAG = Boron Steel 2 mm (MAG Welding)
Hybrid = Boron Steel 0,68 mm (Hybrid Laser Welding)

Price of cutting gas, PG_C = 2 €/m³
Price of laser gas, PG_L = 25 €/m³

Consumption of cutting gas,
$CG_{C\ MAG}$ = 2500 l/h
$CG_{C\ Hybrid}$ = 2100 l/h

Consumption of laser gas,
$CG_{L\ MAG}$ = 200 l/h
$CG_{L\ Hybrid}$ = 160 l/h

Cost of gases,

$$CG_{MAG} = \frac{\left(CG_C \cdot PG_C + CG_L \cdot PG_L\right)}{1000} = 10\ € / h$$

$$CG_{Hybrid} = \frac{\left(CG_C \cdot PG_C + CG_L \cdot PG_L\right)}{1000} = 8´20\ € / h$$

Electrical power consumption,
PC_{MAG} = 37´5 kW
PC_{Hybrid} = 29 kW

Price of electricity,
PE = 0´15094 € / kWh

Number of cut starts per part,

NS_{MAG} = 2

NS_{Hybrid} = 2

Length of cut per part,

LC_{MAG} = (2 · 500 + 2 · 125) + (2 · 500 + 2 · 145) = 2540 mm

LC_{Hybrid} = (2 · 500 + 2 · 125) + (2 · 500 + 2 · 145) = 2540 mm

Price of labour,

PL = 15 €/h

Efficiency,

η = 80%

Speed of cutting,

SC_{MAG} = 3 m/min = 50 mm/s

SC_{Hybrid} = 4 m/min = 66´67 mm/s

Time of cut Start, penetration and movement,

TM_{MAG} = 2 s

TM_{Hybrid} = 1´5 s

Total time of cuts starts,

TS_{MAG} = NS · TM = 2 · 2 = 4 s

TS_{Hybrid} = NS · TM = 2 · 1´5 = 3 s

Total time of cutting,

$$TC_{MAG} = \frac{\left(\frac{LC_{MAG}}{SC_{MAG}} + TS_{MAG}\right)}{\eta} = 68´5 \text{ s} = 0´019 \text{ h}$$

$$TC_{Hybrid} = \frac{\left(\frac{LC_{Hybrid}}{SC_{Hybrid}} + TS_{Hybrid}\right)}{\eta} = 51´37 \text{ s} = 0´014 \text{ h}$$

Total cost of labour,

$CL_{MAG} = PL \cdot TC_{MAG} = 0´285$ € / part

$CL_{Hybrid} = PL \cdot TC_{Hybrid} = 0´21$ € / part

Total cost of electricity,

$CE_{MAG} = PC_{MAG} \cdot PE \cdot TC_{MAG} = 0´11$ € / part

$CE_{Hybrid} = PC_{Hybrid} \cdot PE \cdot TC_{Hybrid} = 0´06$ € / part

Total cost of gases,

$TCG_{MAG} = CG_{MAG} \cdot TC_{MAG} = 0´19$ € / part

$TCG_{Hybrid} = CG_{Hybrid} \cdot TC_{Hybrid} = 0´12$ € / part

Total cost of the Cutting Process,

$TCG_{MAG} = CL_{MAG} + CE_{MAG} + TCG_{MAG} = 0´56$ € / part

$TCG_{Hybrid} = CL_{Hybrid} + CE_{Hybrid} + TCG_{Hybrid} = 0´39$ € / part

$$\%\text{Cutting Cost Reduction} = \frac{(0´56 - 0´39)}{0´56} \cdot 100 = 30´4\%$$

%Cutting Cost Reduction = 30´4%

• **Bending cost**

Once the sheets are cut, it is necessary to bend them to their final form. Therefore, a cost calculation is done. As you can see below this cost is negligible.

MAG = Boron Steel 2 mm (MAG Welding)
Hybrid = Boron Steel 0´68 mm (Laser Hybrid Welding)

	Tensile strength Rm [Mpa]	Elongation A5 [%]	Hardness [HBW]
Boron Steel 2 mm (MAG)	1200	15	320
Boron Steel 0,68 mm (H-L)	1000	12	250

Table 2: Parameters

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.

$$P = \frac{1{,}6 \cdot b \cdot t^2 \cdot R_m}{10000 \cdot W}$$

Boron Steel 2 mm (MAG)

• Length, b = 500 mm
• Thickness, t = 2 mm
• Ultimate Tensile Strength, Rm = 1200 Mpa
• Bending radius, Ri > 3t = 6 mm
• Die opening width, W = 10t = 20 mm

Boron Steel 0´68 mm (H-L)

• Length, b = 500 mm
• Thickness, t = 0´68 mm
• Ultimate Tensile Strength, Rm = 1000 Mpa
• Bending radius, Ri > 3t = 2´04 mm
• Die opening width, W = 10t = 6´8 mm

Bending force:

$$P = \frac{1'6 \cdot 500 \cdot 2^2 \cdot 1200}{10000 \cdot 20} = 19'2 \text{ tonnes}$$

$$P = \frac{1'6 \cdot 500 \cdot 0'68^2 \cdot 1000}{10000 \cdot 6'8} = 5'44 \text{ tonnes}$$

The hydraulic press brake:

In the next table is possible to see the features of the different kind of presses. The model G-2550 has been selected due to the characteristic of the process [5].

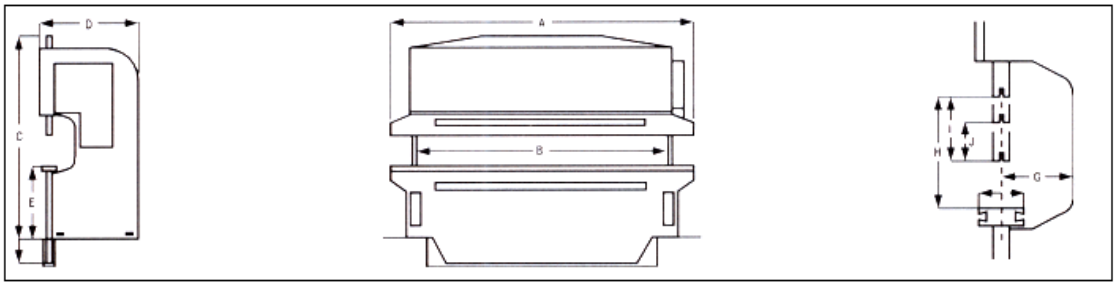

Figure 6: Hydraulic press brake scheme

Model	Max. Power TN	Length A mm	Distance Between Studs B mm	Total Height C mm	Total Width D mm	Height from the floor to the table E mm	Goose Neck Depth G mm	Distance from the table to the board H mm	Board Stroke I mm	Adjustment over the top J mm	Table Width K mm	Raising Force T TN	Number of Cylinders	Approach Speed mm/seg.	Bending Speed mm/seg.	Return Speed mm/seg.	Main Engine CV	Weight TN
G-2050	50	2000	1600	1750	1000	800	200	300	150	75	130	4	2	70	7	50	4	2
G-2550	**50**	**2550**	**2100**	**1850**	**1000**	**800**	**200**	**300**	**150**	**75**	**130**	**4**	**2**	**80**	**7**	**50**	**4**	**3**
G-3050	50	3100	2600	1850	1000	800	200	300	150	75	130	4	2	100	7	50	4	3

Table 3: Hydraulic press brake features

Angle of bend: α

Angle: 90º

Spring back: 11°-18° ~ 15º

Angle of bend = Angle – Spring back = 75º

Bending distance: d

MAG: tg (α/2) = (W/2)/d $\rightarrow$ d = (20/2)/tg37´5 = 13´03 mm

Hybrid: tg (α/2) = (W/2)/d $\rightarrow$ d = (6´8/2)/tg37´5 = 4´43 mm

Bending time

Bending speed: 7 mm/s

Bending time = distance/speed

MAG $\rightarrow$ t_{MAG} = 13´03/7 = 1´86 seconds

Hybrid $\rightarrow$ t_{Hybrid} = 4´43/7 = 0´63 seconds

Cycle time

T = Initial positioning + Bends · (Approach + Bend + Return) + (Bends – 1) · Repositioning + Exit

Initial positioning time = 5 seconds (experimental data)

Approach time= Adjustment over the stop/Approach speed = 75/80 = 0´94 second

Return time = Adjustment over the stop/Return speed = 75/50 = 1´5 seconds

Repositioning time = 1 second (estimated data)

Exit time = 6 seconds (experimental data)

T_{MAG} = 2 · [5 + 4 · (0´94 + 1´86 + 1´5) + 3 · 1 + 6] = 62´40 seconds

T_{Hybrid} = 2 · [5 + 4 · (0´94 + 0´63 + 1´5) + 3 · 1 + 6] = 52´56 seconds

T_{Hybrid} = 84% T_{MAG}

Power of the engines = 10 CV

kWh price, PK = 0´15094 €/kWh

	PRESS			
	Approach	**Bending**	**Return**	**Total time**
MAG	4x2x0´94	4x2x1´86	4x2x1´5	34´4 s
Hybrid	4x2x0´94	4x2x0´63	4x2x1´5	24,56 s

Table 4: Press times

PowerHPB = 10CV $\cdot$ 0´736 $\frac{kW}{CV}$ = 7´36 kW

HPBCost = 7´36kW $\cdot$ 0´15094 $\frac{€}{kW \cdot h}$ = 1´11 $\frac{€}{h}$ = 3´08 $\cdot 10^{-4}$ $\frac{€}{s}$

MAG = 3´08 $\cdot 10^{-4}$ $\frac{€}{s}$ $\cdot$ 34´4 $\frac{s}{part}$ = 0´0106 $\frac{€}{part}$

Hybrid = 3´08 $\cdot 10^{-4}$ $\frac{€}{s}$ $\cdot$ 24´56 $\frac{s}{part}$ = 0´00757 $\frac{€}{part}$

%Bending Cost Reduction = $\frac{(0´0106 - 0´00757)}{0´0106} \cdot 100$ = 28´59%

%Bending Cost Reduction = 28´59%

- **Welding cost**

Finally, welding process cost is studied. In this case, the most important parameter is not thickness but welding method.

MAG welding cost:

Operator factor, OF = 0´85 (this factor has been improved with an assistant)

Welder cost, WC = 30 €/h

Assistant cost, AC = 18€/h (he prepares the parts while the welder is welding)

Velocity of welding, VW = 0´09 m/min

Cross-sectional area, A = 0´06 cm² + 10% = 0´066 cm²

Velocity of deposition, VD = 2 kg/h

Deposition efficiency, DE = 0´95

Filler metal price, FP = 15 €/kg

Shielding gas price, GP = 11 €/m³

Shielding gas flow rate, GF = 0´36 m³/h

Power of the MAG equipment, P = 3 kW

kWh price, PK = 0´15094 €/kWh

Deposition rate,

DR = A · ρ_{Steel} = 0´066 · 10^{-4} m² · 7850 kg/m³ = 0´05181 kg/m

Time per part,

$$T = \frac{DR}{VD} \cdot L = \frac{0´05181 kg/m \cdot 3600 s/h}{3 kg/h} \cdot 0´28 m = 17´41 \text{ s}$$

Labour cost,

$$LC = \frac{(WC + AC) \cdot DR}{VD \cdot OF} = 1´4629 \text{ €/m}$$

Filler metal consumption,

$F_c = \frac{DR}{DE}$ = 0´05454 kg/m

Filler metal cost,

$F_C = FP \cdot F_c$ = 0´8181 €/m

Shielding gas cost,

$GC = \frac{GP \cdot GF}{60 \cdot VW}$ = 0´73 €/m

Power cost,

$PC = \frac{DR}{VD \cdot OF} \cdot P \cdot PK$ = 0´014 €/m

WeldingCost = LC+FC+GC+PC = 3´025 €/m · 0´28 m/part = 0´85 €/part

Total Welding cost = 0´85 €/part

Hybrid Laser welding cost:

Operator factor, OF = 0´95 (this includes total automation, tooling in peak condition, flat position of welding, etc.)

Operator cost, OC = 15 €/h
Velocity of welding, VW = 0´6 m/min
Cross-sectional area, A = 0´0204 cm² + 10% = 0´0224 cm²
Velocity of deposition, VD = 11´5 kg/h
Deposition efficiency, DE = 0´90
Filler metal price, FP = 12 €/kg
Shielding gas price, GP = 8´05 €/m³
Shielding gas flow rate, GF = 0´9 m³/h
Power of the laser equipment, P_l = 6 kW
Power of the MAG equipment, P_M = 3 kW
kWh price, PK = 0´15094 €/kWh

Deposition rate,

DR = A · ρ_{Steel} = 0´0224 · 10^{-4} m² · 7850 kg/m³ = 0´01758 kg/m

Time per part,

T = $\frac{DR}{VD} \cdot L$ = $\frac{0´01758 kg/m \cdot 3600 s/h}{11´5 kg/h}$ = 5´5 s/m

Labour cost,

LC = OC · T = 15 €/h · $\frac{5´5 s/m}{3600 s/h}$ = 0´0229 €/m

Filler metal consumption,

F_c = $\frac{DR}{DE}$ = 0´0195 kg/m

Filler metal cost,

F_C = FP · F_c = 0´234 €/m

Shielding gas cost,

GC = $\frac{GP \cdot GF}{60 \cdot VW}$ = 0´201 €/m

Power cost,

PC = $\frac{DR}{VD \cdot OF} \cdot (P_l + P_m) \cdot PK$ = 0´002186 €/m

WeldingCost = LC+FC+GC+PC = 0´46 € / m · 1 m/part = 0´46 €/part

Total Welding cost = 0´46 €/part

%Welding Cost Reduction = $\frac{(0´85 - 0´46)}{0´85} \cdot 100$ = 45´88%

%Welding Cost Reduction = 45´88%

Summary of Costs

An outline of the costs is given below. As you can see, the thickness reduction will produce a total cost reduction around 54%.

	Boron Steel 2 mm (MAG)	**Boron Steel 0´68 mm (L-H)**
Raw material	1´91 €	0´65 €
Cutting	0´56 €	0´39 €
Bending	0´0106 €	0´00757 €
Welding	0´85 €	0´46 €
TOTAL	**3´33 €**	**1´51 €**

Table 4: Summary of costs

$$\%\text{Total Cost Reduction} = \frac{(3´33 - 1´51)}{3´33} \cdot 100 = 54´65\%$$

$$\%\text{Welding Cost Reduction} = \frac{(0´85 - 0´46)}{0´85} \cdot 100 = 45´88\%$$

$$\%\text{Bending Cost Reduction} = \frac{(0´0106 - 0´00757)}{0´0106} \cdot 100 = 28´59\%$$

$$\%\text{Cutting Cost Reduction} = \frac{(0´56 - 0´39)}{0´56} \cdot 100 = 30´4\%$$

$$\%\text{Raw material Cost Reduction} = \frac{(1´91 - 0´65)}{1´91} \cdot 100 = 65´9\%$$

3. Conclusions

- Changing welding method to Hybrid Laser let a thickness reduction around 65%.
- The total cost reduction is 54´65%.

4. References

[1] ASM HANDBOOK, Volume 6; Welding, brazing, and soldering (1993)

[2] Rúa Collazo, Germán; Manufacturing sustainability and reengineering analysis of a crane boom member.

[3] Karlsson, Jan; Two laser welding cases and suitable documentation methods.

[4] D. Radaj, C. M. Sonsino and W Fricke; Fatigue assessment of welded joints by local approaches (Second edition).

[5] Web sites:

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