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Bifocal Hybrid Laser Welding

A Technology for Welding of Aluminium and Zinc-Coated Steels

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Abstract

This doctoral dissertation presents the process innovation of Bifocal Hybrid Laser Welding (BHLW) and its application for highest quality seams in welding of aluminium, zinc-coated steels, and its potential for the welding of other materials. Over the last decade a plethora of process models has been conceived for fusion welding of aluminium. The respective empirical process models claim one of the following mechanisms as the cause for instabilities: intensity distribution fluctuations, deformation of the geometry of the keyhole, resonant vibrations within the melt pool, or detrimental physical properties of the melt. Although these empirical models are hardly senseless, this dissertation shows that none fully accounts for the formation of instabilities. State-of-the-art process technology for laser welding of aluminium and zinc-coated steels are detailed: gas metal arc welding, laser augmented arc welding, and multiple or specifically Twin Spot welding. For the last two technologies the results of individual benchmark studies are presented to allow for a fair comparison with BHLW for the reference alloy used in this dissertation.

A novel empirical process model for coated materials is developed herein. This model is predicated on a new categorisation of welding materials; the traditional one – according to their metallurgy – is replaced by one based on laser weldability. This new empirical process model rests on two propositions. The strata proposition accounts for surface coatings such as zinc and aluminium oxide. This proposition is based on an empirical observation previously unreported to account for instabilities: obstruction of the keyhole orifice by surface oxide of aluminium. The influence of vapour explosions inducing instabilities is expressed in the phase transition proposition. The explanatory amendments accompanying each individual proposition supply rules for the laser welder to design the process to counteract instabilities. The influence of invasive process gas shielding causing process pores in laser welding by a straw effect within the keyhole leads to a caveat concerning process gas; this caveat is based on empirical observations derived from in-situ high-speed x-ray photography. Based on these observations, a new empirical process model for laser beam welding of aluminium is developed accounting for all hitherto inexplicable phenomena for welding in vacuum and with nitrogen as shielding gas. Consistent with the empirical data a novel analytical mathematical-physical process model for the formation of gas porosity in aluminium is presented to amend the mathematical process model developed over the last few decades.

In a digression, ancillary technology for BHLW is presented that puts the new empirical and mathematical model to the test. To counteract the cause of porosity, as described by the gas entrainment caveat, a novel coaxial nozzle system for perfect shielding – as to which, if inert gases are used, gas is saved – during laser welding is introduced. By virtue of this nozzle system pores in aluminium can be eliminated, a fact that distinguishes this innovative coaxial nozzle system from state-of-the-art nozzles. This experimental result both verifies the empirical process model and validates the analytical mathematical-physical process model. All that is to the good, but note that the nozzle system is an innovation in itself as it allows for a minimum reduction of inert gas consumption of 60% and carcinogenic NO_x-emissions are simultaneously extinguished, again, in contrast to state-of-the-art nozzles. This is most welcome in light of increasingly stringent European regulation as to occupational exposure limits.

Proven process synergies warrant terming BHLW a ‘hybrid’. The doubling of process efficiency of BHLW as compared to its constituting laser welding processes – namely, HPDL and Nd:YAG laser welding – comes to explain the synergies observed in BHLW: increase of welding speed and penetration depth, reduction of porosity, and superior surface quality. Advantages of BHLW, not to be confused with synergies, and later treated separately, follow: robustness, segmentation of seams by avoidance of stop crater cracks, and defect-free seams in zinc-coated steels. Flawless welding of zinc-coated steels is a singular contribution to production engineering. Later the system technology of BHLW is presented. A sustainable prototype optic head was constructed for BHLW to be applied in industrial circumstances. The innovations in system technology of the optic head are these: easy adjustment of dichroic mirror mount by novel frame-in-frame gimbal construction and a beam trap utilizing a novel absorptive coating.

Filler material is necessary for some alloys of aluminium to avoid hot cracking. A novel filler dilution formula is deduced to adjust the process variables and filler feed rate to prevent cracks. The application of this filler dilution formula establishes that the process technology of BHLW generally reduces the absolute crack susceptibility of alloys, which, being sensitive, are otherwise very likely to crack due to the heat of laser beam welding. Further, BHLW is the first technology truly to ensure a continuous transfer of filler wire without droplet formation. In sum, an inexpensive and safe quality control of filler fire supply by an indicator current enables the foregoing complex optical signal processing.

Finally, the ramifications of the innovative BHLW for production and laser industry in Germany are discussed.

How to read this dissertation

This dissertation presents the state-of-the-art of research and technology in such a way as to advance modestly the subject by prolegomena on terminology and experimental method in welding technology in chapter 2 and by reiterated remarks on methodology whenever this is warranted by what is derived from the received literature. This knowledge establishes a framework to categorize, distinguish, and subsume the plethora of empirical and mathematical process *models* of instabilities found in the literature as described in section 3.1. Each empirical model is treated in isolation, and each is shown to be defective. However, an empirical process model has to be kept apart from the empirical results of its associated process technologies. The model may indeed have been misconceived, yet the welding results of a designed process based on its technology could surprisingly have their merits. Therefore, the results of process *technologies* are presented separately. In order to compare objectively the welding results of these competing technologies to BHLW, individual benchmark studies were conducted. In these studies, welding results for arc welding, laser augmented gas metal arc welding, and Twin Spot laser welding of aluminium were generated for the *reference* alloy used within this dissertation employing the same monitoring and preparation methods and devices as for BHLW. Since the reference alloy is an extrusion alloy, hardly any data for the reference alloy could be found in the literature. Extrusion alloys are notoriously difficult to fusion weld as detailed in paragraph 8.2 due to their susceptibility to cracking. EN AW-6060 is a challenging alloy in fusion welding and was *not* selected to be the reference alloy to put state-of-the-art process technologies and BHLW to a discriminating test but rather to satisfy the requirements of the collaborative research centre SFB/TR10. The objective of this SFB, which is kindly supported by the German Research Foundation (DFG), was the “integration of forming, cutting, and joining for the flexible production of lightweight space structures“.

The production of aluminium profiles is an economical and well-established industrial process. The creation of value by assembling such profiles to lightweight space-frame structures hinges on a flexible joining technology. Laser welding can eliminate flanges and satisfies the demand of lightweight construction. LBW is evidentially advantageous as a technology for the challenge of *fusion* welding of aluminium. However, the intrinsic problems encountered in fusion welding of *aluminium* must be solved. Although the process technologies of arc welding, laser augmented gas metal arc welding, and Twin Spot laser welding *are* state-of-the-art technologies, the welding results for the *reference* alloy and for zinc-coated steels of these technologies are scantly represented in the literature. Thus, the results of the benchmark studies of those technologies presented in paragraph 3.2 represent an *original* contribution to the state of research of laser beam welding, which is dealt with throughout chapter 3. For the remaining process technologies of multiple spot laser welding, oscillation and laser stir welding, and beam amplitude modulation welding, which are also featured in paragraph 3.2, benchmark studies could not be conducted as these technologies were unavailable commercially, the author not excepted. The results for other aluminium alloys and zinc-coated steels, other than the reference materials considered in this dissertation, are gathered from the literature and presented in such a way as to substantiate well-informed speculation regarding how the reference materials might behave for these process technologies as compared to BHLW. The reader must concur or not with these arguments after deliberation. The results of BHLW are briefly stated there and are detailed later, in chapters 6 and 7.

In order to understand the process of BHLW, the constituting processes are briefly described. New experimental results are presented to the reader in paragraph 4.1, though conduction mode welding (CMW) by high power diode lasers (HPDL), keyhole welding by the Nd:YAG laser, and influence of process gases have been well researched over the last few decades. Thus, a *phenomenological* account to understand deep penetration welding by BHLW is given. The interpretation of this phenomenological evidence represents *fundamental* knowledge for the reader to appreciate the development of a novel empirical process for laser beam welding of aluminium and other coated materials. This model is encoded in *abstract* propositions. The experimental evidence very briefly rears its head but is later described in detail in chapters 6 and 7. It is left to the reader to judge whether the new process model ought to be accepted. However, as the experimental evidence of the *effects* of BHLW is presented without reference to the model, the merits of BHLW should not called into question if the *causes* thought to arise from the model are overhauled or rejected in the future.

Before the results of BHLW are presented a *digression* on ancillary technology is inserted. The reader only interested in the technology of BHLW might skip chapter 5, a self-contained discussion of shielding gas nozzle, though the chapter does advance welding technology; it is given in the interest of thoroughness. Its results are later quoted in chapters 6 and 7 on the synergies and advantages of BHLW. The digression will surely be of interest to the scientific reader.

In chapter 8 the system technology of BHLW is detailed. The continuity of filler wire supply is an easy means of quality control of filler transfer, suggesting an economic case, which is briefly outlined for the reader’s own appraisal. As most chapters on BHLW are interconnected, *forward* references are in some cases unfortunately unavoidable. Results denoted by these references are generally the final upshot of a topic; whether or not the reader checks the later pertinent chapter immediately, the reader can *trust* that they will be satisfactorily established.

1 Introduction

1.1 Lasers are a key technology in the present

LASER is an acronym for light amplification by stimulated emission of radiation. But what *is* light? Light is *the* fundamental entity. In one notion, light was the first entity to be called into existence: "Let there be light" [GOD, p. 1]. In another notion the beginning of the universe was dominated by light or photons according to current theories in cosmology [LONGAIR 2003, p. 535].

More down to earth, lasers constitute a commonplace technology. Whether we are conscious or not of their being mundane depends on our understanding of the word *light* in what constitutes a laser. Light designates the visible range of the electromagnetic spectrum. Although the first laser ever built by Maiman [MAIMAN 1961] emitted in the visible range, Albert Einstein's theory, which describes its physical principle, is by no means limited to *light* but applies to *radiation* in general. In fact, most modern lasers do *not* emit in the visible part of the electromagnetic spectrum. The term 'laser' is misleading - it encourages misconceptions. Putting aside superficial aspects of the laser's history militates in favour of calling it today what it actually is:

electromagnetic radiation amplification by stimulated emission of radiation,

namely: ERASER.

The acronym '*eraser*' is a pun and does not allude to the *power* of the radiation those systems generate, but 'eraser' is very descriptive. However, the author will regrettably use the nowadays more conventionally acceptable acronym 'laser' instead of the precise 'eraser'. The properties of the radiation are characteristic of lasers. Their radiation is monochromatic, exhibits little divergence, and is temporally and spatially coherent. There are laser systems, which are subsumed in this category, whose radiation is neither stimulated nor amplified. Emitting semiconductors assembled in high power diode laser are exemplary. LEDs should therefore be treated as sources of laser radiation since their radiation is monochromatic and shows, within certain limits, reduced divergence.

Keeping this in mind one should reconsider and, it is hoped, broaden one's views of lasers. Lasers are an integral part of everyday life. Most little flashing lights are actually sources of radiation that have the properties characteristic of lasers. They are built into CD players, handyman tools to regulate water levels, and even cutting-edge kitchens in London where they are used by prominent gourmet chefs [KALWA 2005].

This is contrary to the use of lasers in films other than documentaries. In science fiction and other imaginative works, lasers serve as a symbol of inexplicable powers. In Star Wars villains cut other beings heads off with a 'laser sword', and James Bond was almost cleaved in half by Goldfinger's laser. Never mind that in reality the Star Wars swords are pyrotechnic effects and that the laser that seared through the gilded plate to which 007 was chained was actually an acetylene flame. However, though these pictures were fictional at the time they were being shot, what they envisaged is reality *now*. Laser beams have been developed to serve as defensive weaponry. Ballistic missiles are to be destroyed in the stratosphere by stupendous laser beams. Needless to say, lasers were capable of cutting and welding metal just a few years after Goldfinger's premiere. Seeming fantasy can indeed pave the way to the breakthroughs now shaping our reality. Such fantasy serendipitously points the way to the innovations shaping our reality.

1.2 The future is 'Laser Age'

The history of civilization can be divided by the technology extant in each epoch: The Stone Age was followed by the Bronze Age and then the Iron Age. And knowledge and technology appear to accelerate as age follows age. The industrial revolution was followed comparatively not long thereafter by the Nuclear Age. Where are we now going?

The ages are normally named retrospectively - later generations appraise their ancestors' times based on the decisive advance the impact of which can be said to have brought about a revolution. Indeed, such an advance is necessary for us to note with clarity the demise or subordination of the old and the dawning of a new age.

Let us consider the current situation and peer into the future in order to guess what age our descendants may judge us to have inaugurated. Within a mere six years of the new millennium, in 2006, the Nobel Prize for physics honoured contributions to the development of laser-based precision spectroscopy including the optical frequency comb technique, the details of which will not herein be given [HÄNSCH 2006]. Suffice it to say that the ramifications of Hänsch’s findings are obvious to the scientifically informed public. The laser frequency comb allows an improvement of at least one order of magnitude in the accuracy of time measurements. This will in due course lead to a greatly enhanced insight into the physics of our world, as did all previous improvements of accuracy. Concurrent with the turn of the century, laser systems capable of output powers of several hundred kilowatts were designed. Their funding may have been due chiefly to their potential use in preemptive missile defence, but they are put to other uses as well.

At the National Ignition Facility (NIF) of the Lawrence Livermore Laboratory, in the American state of California, 192 ultraviolet lasers eventually came to form the world’s largest laser [BIBEAU 2006]. This laser has an output power of 1.8 MJ which will be deposited into a hohlraum target. By 2010 this deuterium-tritium target will be so compressed that it will ignite and burn, which in turn will liberate more energy than is required for the laser to ignite the fusion reaction. The International Thermonuclear Experimental Reactor (ITER) championed by the European Union serves the same objective. Early in the Nuclear Age *fission* provided energy to power our civilization. However, fission creates radioactive waste and the proliferation of this waste engenders the enormous hazard of the potential construction of illicit nuclear weapons. Therefore the nuclear age cast a pall from its inception, and, in the current geo-political climate, fraught as it is with the possibility of additional crises, one cannot be sure how the Nuclear *Fission* Age will terminate, a fact that confounds an assessment now of retrospective judgment decades or centuries in the future. Although nuclear fission does allow for the triggering of a fusion reaction in the form of a hydrogen bomb, it is clear that this energy can be put to entirely peaceful ends. *If* nuclear fusion can be tamed by a controlled reaction in the National Ignition Facility, this would be a scientific achievement unparalleled in world history, one comparable only to stupendous leaps in evolution such as the development of language. It would potentially transform our world for the better.

The Club of Rome predicted in 1972 ‘The Limits to Growth' [MEADOWS 1972, MEADOWS 1974]. And indeed we are now experiencing scarcity of basic commodities with the constant rise in the cost of energy and other resources. An inconsumable, virtually infinite, and emission-free source of energy, which is precisely what fusion would put at our disposal, would enable humanity to commence a new kind of *civilization*. Energy in the coming Nuclear *Fusion* Age will not stem from consumption of *resources*, which are by definition only accessible *locally* or *nationally,* but will be *derived* from *science*, which by definition is shared *globally*. Nuclear fusion will guarantee the welfare of humanity for centuries or millennia. This breathtaking accomplishment, being potentially enabled by laser technology, would earn our transitory age the epithet: Laser Age.

Savour this outcome, because it will solve an immense problem already bedevilling the planet: the shortage of energy.

1.3 Lasers are the key to welding novel materials

Notwithstanding the decisive contribution lasers can make to civilization's advancement, less ethereally, one has to notice the immediate importance of lasers to Germany's economy. Germany lost out in many areas of technology in the past decade or could not capitalize fully on inventions and innovations it generated. Laser technology is an exception. Globally Germany is a leader both in markets and in technology. Its share of the world's laser system market is about 40%. This is a tremendously enviable situation, which can be retained and even expanded. The market research of the Spectaris/VDMA report 2006, however, shows that production is outsourced to countries with lower labour costs. Innovations are crucial if Germany wants to secure and expand its position.

However, innovating is in many cases difficult. Take welding, which is an ancient technology. In antiquity some regarded Glaukos of Chios to be the inventor of welding. He produced a vessel by *solid phase joining*, that is, by a blacksmith hammering two iron pieces together. After that seminal event, innovations were extremely slow-paced [AICHELE 2005].

Today welding can be described as the joining of two components by coalescence of the surfaces in contact with each other. This coalescence can be achieved by melting the two parts together, termed *fusion welding*, or by bringing the two parts together under pressure, perhaps with the application of heat, to form a metallic bond across the interface.

This glacial progress is true even in our day. Classical arc welding has experienced only small steps forward in the past decade. Electron beam welding allowed welding of joints of high aspect ratio (c.f. equation 3.3) in vacuum. The advent of high-power laser systems manifested additional progress. In laser welding technology each new laser system available facilitated novel processes. For industrial laser welding the following systems were chronologically employed: CO_2 lasers, Nd:YAG lasers, high power diode lasers (HPDL), and - at this writing - disc or fibre laser technology is being considered.

However, for welding, the weld*ability* of the materials to be joined is a prerequisite; where it is lacking, even elaborate welding technology seemingly cannot compensate. Very much the same holds for any other joining technology; indeed, the pivotal point for introduction of new materials into a production chain is the joining technology. Unfortunately, this is not always borne in mind when novel materials are designed. Semi-finished products, such as sheets or profiles, which cannot be joined, can never become products. Adequate joining technologies are absent for many materials. Hence, they have been developed in vain because they cannot be used.

This is notable for the application of aluminium in car body manufacturing. Forecasts suggest that Europe and North America will retain the biggest shares of the global automotive market until 2011 or later. Thus, most car manufacturers try to satisfy the demands of both markets to maximize the number of potential customers. And most European car producers are as much dependent on their North American as on their home markets.

In late 2004 the U.S. Secretary of Transportation proposed a major regulatory upgrade in side-impact crash protection for all passenger vehicles [INTERNET 1]. Accordingly, Federal Motor Vehicle Safety Standard 214 is about to be strengthened with consequent requirements for crashworthiness. Passive security systems alone will not meet the demands of this new dispensation. Indisputably the space frame and body shell will have to be toughened to absorb the additional distortional energies. It seems inevitable that the car chassis will weigh more.

Europe has bound itself to reduce overall CO_2-emissions to fight climate change. The 2007 Bali agreement, which followed up on Kyoto, may or may not be implemented worldwide: On the one hand, pressure from environmentalist groups is formidable; on the other hand, costumers are seeking more economical vehicles since fuel prices are high owing both to the high price of oil, now at a decade-high, and to petroleum taxes.

To meet these demands the automotive industry has to pursue two diametrically opposed aims. In the USA vehicles need to be much tougher, meaning heavier, but, in Europe, lighter, in order to consume less fuel [ZÄH & TRAUTMANN 2005].

Light-weight design and further application of light-weight alloys can deal with this predicament by reducing weight as well as increasing strength. Light-weight material and design construction can cut the Gordian knot of these seemingly contradictory demands. Hence, joining techniques are needed that satisfy the requirements of modern vehicle manufacturing [Zäh & Trautmann 2004].

These techniques need to be reliable and robust. They need to yield structures that can be mass-produced in such a fashion as to ensure quality control that can be monitored by sensor systems [Zhao 1990]. They need to meet the disparate expectations of both corporations – which seek profits – and consumers – who aspire to thrift. Thus, the new technologies will be scrutinized by manufacturing, economics, and sales.

The objective of this dissertation is to present an innovative process in laser technology for **robust** and **stable** welding of *all* alloys of aluminium *and* of zinc-coated steels. The process is termed Bifocal Hybrid Laser Welding (BHLW), as it utilizes two separate laser sources, namely an Nd:YAG laser and an HPDL. These laser sources can be independently focused on different focal planes: the system is thus termed *bifocal*. The lasers interact in the same process zone; hence, they constitute a *hybrid*. Proven synergies are presented to justify indisputably the designation of the process as ‘hybrid’, a designation that seems, in other contexts, to have been misplaced or which has been used hyperbolically. Additionally, advantages of BHLW for process robustness are detailed to convince the reader of its unparalleled successes in contrast to other laser welding techniques.

1.4 Current laser sources and their system properties

In figure 1.1 the commonly available laser sources for welding are shown. They are characterized by their wavelength, which is typical of their laser active medium.

Figure 1.1: Technical digest of laser systems and comparison to a gas metal arc welding system

For scientific investigations the quality of the beam is of primary interest. It is described by the M^2 factor:

$$M^2 = \frac{1}{K} = \frac{\pi}{\lambda} \cdot \frac{d_0 \cdot \theta}{4} = \frac{\pi}{\lambda} \cdot q \qquad \text{(Equation 1.1)}$$

where M^2 is the beam quality factor, K is the beam propagation factor , λ is the wavelength of the laser (m), d_0 is the diameter of the beam at the beam waist (m), θ is the angle of divergence (mrad), π is Archimedes' or Ludolph's constant, q is the beam parameter product (mm * mrad). The M^2 factor is defined for a diffraction-limited Gaussian beam [DIN ISO 11146-1].

With regards to manufacturing, secondary virtues of individual laser systems play a key role. For brevity's sake only continuous wave (cw-lasers) are considered. The CO_2 laser can provide multi-kilowatt output powers at excellent beam quality. Its wavelength does not permit efficient fibre transmission; mirror guiding systems are needed which infringe on flexibility during production when flanged to a robot arm. Yet the CO_2 laser is the most common laser in manufacturing. High power diode lasers are assembled from semiconductor LED's; their wall-plug efficiency is superior as they lack a resonator medium which degrades electro-optic efficiency. However, their beam quality is poor. The stack by which the LED's are interconnected can be mounted to a robot arm. Such a directly emitting laser permits beam formation - rectangular intensity distributions as well as rotationally symmetric intensity distributions in diode ring laser setups - according to need. Its radiation can be delivered via a fibreoptic cable but only at the cost of a power loss of approximately 25%. The Nd:YAG laser is a classical slab laser, which provides superior beam quality at a very low wall-plug efficiency and can be easily guided by fibres. Disc and fibre laser system were just recently cleared for application in manufacturing. Both systems are distinguished by their excellent beam quality and can be delivered by fibreoptic cable. A disc laser is scaled in power intervals based on how many active discs are combined within the system. A fibre laser is made up of individual single or multimode fibre laser modules, whose feeding fibres are spliced together to achieve the output power desired. The maximum attainable output power and beam parameter product appear to be inversely proportional and can be varied within certain limits according to the manufacturing objective. The fibre laser is more flexible with regards to selection of beam parameters and output powers than the disc laser. The system technology of fibre lasers facilitates later up-scaling if necessary.

2 Prolegomena on Terminology and Experimental Methods

It has been shown above that the acronym ‘laser’ does not fully convey the properties that are actually characteristic and typical of itself – eraser is more apt. The term, ‘laser’ potentially misleading for many, is especially so for persons unfamiliar with the subject, a group constituted in no small part by students. Like confusion prevails regarding the word “hybrid”. Indeed, it seems to have transmogrified into a fancy label for almost anything to which attention is sought to be drawn.

‘hybrid’ is used in science to designate the crossbreed of two distinct entities, such as the hybridization of genes of different origin in microbiology, to create a new united entity by advantageous *interaction*. The mere combination of two processes does not make up a ‘hybrid’ but only represents augmentation without interaction. Hence, whether a combination of two processes constitutes a hybrid depends in turn on whether the combination *transgresses* the sum of the constituting processes. In a word: The whole must be more than the sum of its parts.

Hence, the epithet ‘hybrid’ inherently demands a synergy. In laser welding, ‘hybrid’ habitually refers to the combination of gas metal arc welding (GMAW) with laser deep penetration welding. However, as will be argued in paragraph 3.2, this is not a true hybrid because claimed synergies do not seem to materialize. The laser beam does nothing more than support the arc process by advantageous redistribution of melt. Again, this terminology is misleading since the ‘hybrid’ evidentially is not a true one but merely an arc welding process supported by laser. It is therefore called laser augmented GMAW welding herein.

This dissonance is implicated in the experimental methods used by numerous experimenters. In this context the notion of *ceteris paribus* conditions - all other things being equal - should be noted. Varying one parameter while keeping the others fixed does not in all cases allow comparison of results as normalization might be necessary for this objective. For example, when measuring the heat released on variations of the speed of LBW in a given workpiece one must be cognisant of the *relative* flow of process gas. Helium is a better cooling agent than argon due to its high volatility. When the speed of welding is increased, the flow of process gas must be increased also in order to *normalize* its cooling effect

3 State of Research and Technology of Laser Beam Welding of Aluminium

3.1 Process models of instabilities

In this chapter the state-of-the-art of process models of instabilities is dealt with. The major propositions of these models are enumerated and discussed with regards to the references. Some of these models sparked the development of novel process technologies to counteract instabilities. The results of these welding technologies might be significant even if the process technology was based on a defective process model. Their experimental results are treated separately since these technologies might have their practical merits.

3.1.1 Introduction to process modelling

The modelling of laser beam welding (LBW) can be subdivided into two major classes: empirical and mathematical process models.

Empirical process models are based on *intuitive* concepts that stem from empirical process monitoring, *in-situ* by high-speed photography, or x-ray imaging. Empirical observations also originate from *a posteriori* interpretation of cross-section macrographs, x-ray photography, ultrasonic testing, and EDX-analysis of element content distribution or from other sources.

This is to name but a few hitherto employed techniques in the empirical analysis of laser beam welding. The accuracy and quality of pictured data is strongly dependent on the technical capabilities of the technology with which it was visualized. The in*sight*, which this data provides, can be altered or even changed when the technology of its visualization is refined. The interpretation of these snapshots of welding processes leads to the formulation of an abstract empirical process model.

Such a model is represented by a *common set of rules of behaviour*. This set of rules represent the propositions of the model. The notion of rules suggest that *equivalent* species behave according to the same common set of rules under *comparable* (or *ceteris paribus*) conditions. These conditions are set by the intensity distribution created by the specific laser, the shielding gas, and the welding speed. Hence, these models tacitly imply *categories* in which the species involved and the conditions imposed can be subsumed.

Positively, the utility of such empirical process models rests upon their ability to predict the behaviour of cases, which were hitherto not assayed. These models enable an *extrapolation* of behaviour within the limits of their applicability set by their categories and rules. *Negatively*, if the processes suffer from problems rife in LBW such as formation of humps, pores, and spatter, empirical process models suggest how to design a counteracting technology. The process technologies of laser augmented GMAW, laser stir, and oscillation laser welding (c.f. paragraph 3.2) were developed with explicit reference to a specific empirical process model of *instabilities*, i.e. as formation of humps, pores, and spatter.

This chapter attempts to state the descriptive rules of behaviour of the empirical process model for LBW of aluminium to explicate the categorization of the species employed. This chapter tries to clarify which conditions can be assumed to be *ceteris paribus*. The empirical models will be validated by their *success* in extrapolation, i.e. achieving desired results, or by their *ability* to lead to the development of technologies counteracting undesired behaviour.

Mathematical process models are based on the laws of physics. They *vary* according to the laws of thermodynamics governing LBW and can be assumed to be *a priori*, because these laws have never been falsified. If the theoretical reasoning is stringent and complete in the sense that all simplifying assumptions are stated, the equations expressing the associated dependencies should not be readily cast with doubt. Whenever they are made quantitative, they rest upon the accuracy of those natural and material *constants* entering the calculation. The values of those constants are determined by experiments. Hence, they represent a possible source of error. One has to bear in mind that the *concept* of constants in the realms of physics eventually means that within the theory sustained they are regarded as *unchangeable*. They are only measured to a certain degree of accuracy. The experiments suffer from certain shortcomings (c.f. paragraph 5.2) imparting errors on the magnitudes measured. Or as far as material constants are concerned, their values vary from one alloy of aluminium to another or even more malignantly from batch to batch for a given alloy. Although a very accurate measurement is necessary to quantify the mathematical model, these measurements are often too time and money consuming to be carried out for each individual case.

The *success* of such a mathematical process model is determined by the degree of congruence with the experimental measurements, i.e. how good it ‘fits’ and therefore *explains* the data. It is sometimes not easy to test the equations of a mathematical process model against experimental data in cases where these formulas are not *analytical*. The method of finite elements (FEM), which requires a *numerical* solution at discrete points being meshed according to interest, reaches a compromise between a desired accuracy, which is scaling with the interstitial distance within the mesh, and the processing resources of the computers deployed. But even by *simulating* the continuity of solutions of functions by fitting up the FEM discretization, the results could not always be matched with experimental data [DAVÉ 2003].

At this point a caveat should be stated: the above is not intended to cast doubt on the fact that mathematical process models *do* actually fit experimental data and that they explain this data by *deduction* from the underlying laws of physics; this is most positively stated. It is merely pointed out that it may be difficult to establish the *success* of a mathematical model owing to the complexity of calculus and inaccuracy of constants measured. If the mathematical process model can easily be quantified and does nonetheless not fit the experimental data, the experiment needs to be critically questioned and not the mathematical process model, which is deduced from the laws of physics.

In this chapter some mathematical process models for LBW are presented and the assumptions on which they are based. It is shown that the problems of these mathematical models, when applied to LBW of aluminium, root in a misconceived design of experiment. Such models can be mathematically correct but whether they mirror empiric reality is difficult to comprehend. In paragraph 4.3 the author will present his mathematical process model for process gas porosity formation in LBW of aluminium.

3.1.2 Empirical process modelling of instabilities

In this dissertation *any* seam imperfection introduced by the welding process adding to blow holes, pores, and spatter is subsumed in the general *category* of ‘instability’. Rapp *claimed* that all these instabilities are just different manifestations which originate from the *same* physical cause [RAPP 1996, p. 115].

Over the years a plethora of empirical models explaining the instabilities in LBW have been discussed. Seam imperfections in LBW were rife in industry and sparked a lot of research. The approach of this research was *negative*, because the objective was to improve on the empirical process models of *instabilities*. This was seen to be the key to eventually obviate these instabilities by design of an apt process technology, which stabilizes the welding process.

A recent review paper on empirical process models of instabilities is not available since it seems almost impossible to describe all the models in detail. In particular, some authors support opposing views with regard to one aspect of some model but the same idea when it comes to other aspects.

To summarize the state of research the major *conceptual hypotheses* are presented by stating the corresponding **proposition**. The proposition states the *mechanism of instability* which *causes* a seam imperfection in LBW. The authors championing those propositions can be found in the references given.

Instabilities are due to:

Proposition 1: Fluctuations of the intensity distribution on the workpiece

Proposition 2: Deformation of the geometry of the keyhole

Proposition 3: Resonant vibrations of the melt being part of a self-exciting system

Proposition 4: Physical properties of the melt of a specific material

3.1.2.1 Intensity distribution fluctuations

Let us follow the laser beam's path of propagation to consider sources of intensity fluctuations in turn.

Figure 3.1: Laser keyhole welding: beam caustic is indicated by a cone, welding direction out of page alongside elevation

The first source of such fluctuations can be variations of *power emitted* by the laser system:

$$RZ = \frac{\sigma}{\overline{P}} \qquad \text{(Equation 3.1)}$$

In this equation σ is a measure for the power fluctuation represented by the root mean square deviation scaled to the mean power $\overline{P}$ of a given laser system.

4 Bifocal Hybrid Laser Welding (BHLW) of Aluminium

4.1 BHLW process technology for stability in aluminium welding

In this chapter the process technology of BHLW for aluminium is detailed. The stability and robustness of the constituting processes of conduction mode welding by an HPDL and keyhole welding by an Nd:YAG laser are described and analyzed. Two pivotal findings of this dissertation are presented in this chapter: First, the aperiodical closure of the keyhole orifice by the sturdy aluminium oxide layer. Second, the causal effect of the process gas on pore formation is proved. These two findings are especially important for aluminium welding in industrial circumstances where instabilities are rife. The attention is concentrated on aluminium. Steels are considered briefly whenever this is elucidating. The results, synergetic effects, and the system technology of BHLW for aluminium and for other materials are described in chapter 8. At the end of this chapter a novel mathematical process model of the formation of process porosity is attempted.

4.1.1 Conduction mode welding

For conduction mode welding (CMW) the laser beam is focused to a power density of the order of magnitude of 10^3 W mm^{-2}. A power density of this order of magnitude is used to fuse materials to create a joint *without* significant vaporization. The wavelets collapse upon being intersected by the material according to Bohr’s principle of complementarity in the Copenhagen interpretation of Quantum Mechanics. The energy of the wavelets is input by direct heating into the workpiece. The heat flow is governed by thermal conduction from a surface heat source, and the weld is made by melting portions of the base material. These principles are relatively well understood enabling analytical modelling to be applied to joining of metals and alloys.

A hemispherical weld bead and heat affected zone (HAZ) is formed, as can be seen in figure 4.1. Conduction-limited welds exhibit a low aspect ratio according to equation 3.3. Such welds show a broad bead, which is desirable when gaps are to be bridged, but a low depth, which is in some cases deliberately aimed at, e.g. if materials of different thickness are to be welded to highest quality. HPDL systems recommend themselves for CMW as they readily deliver moderate beam quality which is still good enough to melt the material. HPDLs exhibit a very high wall-plug efficiency compared to solid state lasers and are comparably cheap, c.f. table 1.1.

Figure 4.1: HPDL cross-section macrograph of hemispherical weld pool and heat affected zone (HAZ); P_{HPDL}= 3kW; argon flow 20L min^{-1}; EN AW-6060 T66; v_w = 0.5 m min^{-1}

In equation 3.5 the *Peclet number* was introduced as a measure for the importance of convectional flow and heat conduction in the distribution of the radiation power absorbed throughout the melt pool. For a typical case of aluminium welding *Pe* scales with $54.8 \cdot v_w$. In the melt pool induced by an HPDL the velocity of the fluid is considerably higher than the velocity of welding. The velocity of the fluid can be estimated by monitoring oxide particles staying afloat on the melt pool as tracer particles. Hence, the *Pe* is estimated to be about 5 for aluminium indicating that heat is transported by conduction as well as convection. For steels *Pe* scales with $294 \cdot v_w$. Invoking the average velocity in melts, *Pe* is of the order of magnitude of 15. Thus, indicating that in steels convection is dominant. Secondly, the Peclet number provides a measure of the relative effectiveness of heat transport by convection and conduction. Near the fusion boundary of the melt pool the flow of melt is stagnant. Since the Peclet number is one order of magnitude lower for liquid aluminium than iron, heat transfer by conduction is more efficient in aluminium than in steel melts.

Figure 4.2: *Effect of welding with a circular (right) or a rectangular (left) HPDL focal spot: relative intensity distribution not to scale; steel was used to make the dependence of penetration depth on associated melt motion more obvious; parameters of cross-section macrographs (bottom row): P_{HPDL}= 3 kW; argon flow 20 L min^{-1}; v_w = 0.5 m min^{-1}; stainless steel 1.4301(X5 CrNi18 10); right: rectangular spot 1.7 mm x 3.8 mm; left: circular spot diameter 2 mm*

Thirdly, the *Marangoni effect*, i.e. the spatial temperature gradient of the surface tension, creates a driving force by which the melt tends typically to be pulled away from hotter towards cooler regions. During laser welding this surface tension force dominates the flow of the melt.

For a *radial symmetric* Gaussian intensity distribution, shown on the left in figure 4.2, the flow lines describe circles moving up in the middle and being deflected towards the perimeter of the melt pool. The melt is rising up towards the peak of the distribution, since the laser acting as a surface heat source creates the hottest spot there. This leads to an efficient mass transport by convection transferring enough heat into the fusion zone for further melting. The laser needs to be moved along the joint line to weld *linear* seams. The laser constantly alters its position while *transgressing* the workpiece. This effects the flow lines along *this* line of motion. The melt elements at the melting front rise towards the centre peak of the distribution, i.e. *opposite* with regards to the direction of motion of the laser beam, since the peak of the distribution is approaching these melt elements and the heat gradient points away from the peak: In the rest frame of the workpiece the melt elements are *reversed* in direction once the peak of the distribution has transgressed them. This is because once the peak has transgressed these melt the heat gradient still points away from the peak, but the melt element and the peak have exchanged their relative position. Then, for the very same melt element the flow line points *along* the direction of motion. This gives a *net* **stagnant** motion.

In other parts of the melt, i.e. off-axis with regards to the line of linear motion, the melt elements experience radial deflections while in motion. This leads to an overall reduced amount of melt being transported to the boundaries of the melt pool by convectional flow: the melting efficiency is decreased. The weld pools become shallower and broader. This results in a decrease of penetration depth as compared to the rectangular intensity distribution, c.f. macrographs at the bottom of figure 4.2.

A *rectangular* intensity distribution is shown on the right hand side of figure 4.2. In the intensity distribution the slow axis still represents a Gaussian profile, but the fast axis exhibits a smooth top-hat profile. The latter distribution is more efficient for melting. The following account of flow lines and behaviour of melt element motion is based *only* on heat gradient considerations. Again, the flow lines describe circles rising up towards the plane where the peak of the Gaussian lies. It should be noted that there is no significant temperature gradient along the fast axis, because the top-hat axis has a plateau of intensity. The direction of welding is parallel to the fast axis. Hence, when such a heat source is moved along the fast axis the flow lines do not get deflected. The melt elements' motion is mainly restricted to a plane. This plane is parallel to the slow axis and perpendicular to the direction of welding. Such a square or rectangular spot provides conditions for 2D-convectional flow as compared to the 3D-flow pattern for the spherical spot of a radial symmetric Gauss profile. In figure 4.2 the intensity distribution, the flow lines, and the associated cross-section macrographs are displayed. Apart for the intensity distribution the other parameters of welding are equal, i.e. ceteris paribus. The increase in cross-sectional area demonstrates an increase in melting efficiency. The increase in penetration depth should be noted.

For the following results a 3 kW-Laserline HPDL-system with a beam parameter product (BPP) of 85 x 200 mm*mrad was employed. This translates with a spherical lens of $f = 150$ mm into a *rectangular* focal spot of 1.658 x 3.820 mm^2 where the fast axis is aligned with the transverse direction of welding. The wavelengths of the HPDL are centred on 808 & 940 ± 10 nm (FWHM). The compact multi-kilowatt diode laser head can be mounted on an appropriate robot to create a flexible welding tool. When the radiation of an HPDL is coupled to a fibreoptic cable a power loss of approximately 25% is incurred. The caustic and intensity distribution of the head are displayed in figures 4.3 and 4.4.

Figure 4.3: 3D-intensity distribution of HPDL, intensity qualitatively in arbitrary units

5 Shielding gas nozzle for laser beam welding

The often neglected influence of process gas on the result and quality of laser welds has been demonstrated above. The caveat on process gas entrainment in section 4.2.5 sparked the development of an appropriate gas shielding nozzle. Thus, Laval nozzles, which create a supersonic flow, are not considered here. Since no system commercially available satisfied the demand of providing a non-invasive laminar gas flow with respect to the process zone, a new gas nozzle system was designed: This innovative system can perfectly shield the process zone and could therefore serve as a standard system not only for the experiments performed herein but in laser beam welding in general.

5.1 State of research and development

A consistent terminology is needed to avoid confusion within this dissertation, because a plethora of different gas shielding nozzles is documented in the literature. In a *coaxial nozzle* the laser beam propagates through the middle axis of a radial symmetric nozzle. A *lateral nozzle* provides process gas from one side at an angle to the fusion zone. This results in an angle between the direction of beam propagation and the flux normal of the gas. The term *single nozzle* refers to a nozzle geometry which guides one stream of gas or a mixture of gases. A *multiple nozzle* divides up the supply stream of gas into multiple flows of gas, which are guided independently of each other to the process zone. Each gas stream can be a pure gas or mixture of gases. A special case of this nozzle is a *double nozzle* which generates two gas flows. A fluid-dynamical advantageous design of the nozzle contour preventing boundary layer separation and turbulence is termed *laminar nozzle*.

The quotation of the absolute flow measured in litres per minute is clearly not sufficient when different nozzles are to be compared. The flux normalizes the flow with respect to the area normal to the direction of the gas flow and has units of litres per minute per unit area. Thus, it is possible to compare the amount of gas consumption of nozzles with different orifice areas.

Figure 5.1: Map of nozzle concepts

New nozzles concepts developed for laser beam welding normally serve one of the following two objectives: First, by virtue of *geometry* optimization of a single nozzle a pure gas or a gas mixture shall be supplied to the process zone more efficiently than by state-of-the-art single nozzles. Second, *improvement* of gas supply of a pure gas or a gas mixture is aimed at by various designs of multiple nozzles, be they lateral or coaxial nozzles.

Figure 5.1 maps out the concepts of lateral and coaxial gas nozzles. The bottom nozzles represent the most advanced design of the lateral and coaxial nozzle concept found in the literature.

5.1.1 Lateral nozzles

Lateral nozzles – be they single or multiple nozzles - have a significant disadvantage: they are not rotationally symmetric. Laser welding processes are normally performed by robots, because laser radiation is a security hazards for personnel in a staffed production. The programming of weld tracks is more elaborate and accessibility is reduced if the nozzles, which have to come close to the fusion zone, are not rotationally symmetric. Such lateral nozzles are generally tube-like assemblages and are therefore inherently laminar flow nozzles within the limits given by Reynolds number (c.f. equation 5.1). This has been verified by experiments. These experiments additionally show that helium makes an escape upwards before reaching the process zone. The escape of helium is caused by the upthrust it experiences, since its density is lower as compared to ambient air [SEEFELD 2005, p. 998].

It should be noted that such nozzles were tested at a pressure of 3 bar and will therefore invade the melt pool [SEEFELD 2005, p. 998]. Process gas provided in such a way is invasive and leads to increased porosity in aluminium welds. Sadly, Seefeld's paper does not quote the cross-sectional area of the nozzles' apertures. Therefore, the fluxes used cannot be calculated and no comparison of gas consumption can be made.

Caillibotte demonstrated the volatility of helium by means of simulation [CAILLIBOTTE 2004]. The gas nozzle developed by him represents a single lateral nozzle for CO_2 laser beam welding. Caillibotte's nozzle is shown in figure 5.1 f). This tube-like lateral nozzle is designed to minimize the distance between aperture and workpiece. Additionally, the nozzle is cut out in such a way as to admit the unobstructed propagation of the laser beam onto the workpiece. This meanwhile patented nozzle design supposedly provides good process gas coverage of the fusion zone. However, it suffers from a severe drawback: The rim of the nozzle is located only 1 ÷ 2 mm away from the workpiece. Such a small distance makes application in production difficult, since the workpieces need to be clamped for subsequent welding. Therefore, clamping devices need to be positioned close to the future joint. In practice, the workpieces exhibit positioning tolerances. The nozzle devised by Caillibotte would collide if not with the workpiece then with the clamping device. Additionally, Caillibotte only rendered the results of a computer simulation and did not verify this simulation by data from real welding experiments. Instead, he enumerates the problems of lateral nozzles: perturbation of the melt pool, the admixture of air into the process gas, and the positioning of the nozzle to be properly pointed at the melt pool. The inherent angle of inclination of a lateral nozzle with regards to the beam's axis causes perturbation of the melt pool inducing gas entrapment and process porosity. Hence, lateral nozzles, even of the most advanced kind, are no solution of the problem [HÄRTL 2006, p. 41].

5.1.2 Coaxial nozzles

Several coaxial nozzle systems are patented and described in the literature [JP 5050284; JP 7223086; JP 6304777; JP 6304777; JP 11058063; EP 1584406 A2]. They are either single or multiple nozzles and can for reasons of brevity not be detailed here. Some of the patents quoted render guiding mechanisms, e.g. multiple drill holes or slotted holes by which the gas is redistributed before it is blown onto the workpiece [JP 20033181676; EP 0600250].

However, all these designs feature tube-like or conic nozzle contours. They are not fluid dynamically optimized to guarantee a non-turbulent and laminar flow. This is difficult to achieve by a coaxial nozzle, since a tube-like nozzle cannot narrow down its diameter. The diameter is prescribed by the optical system necessary to focus the laser beam. Such nozzles need a high absolute flow rate to create satisfactory fluxes to effectively shield a process zone. The reduction of diameter is limited by the beam caustic for conic nozzle geometries. The conic nozzle geometry will be considered and evaluated as a benchmark for the standard nozzle presented in this dissertation. It will be shown that considerable admixture of ambient air takes place and that perfect shielding of the fusion zone can only be achieved by high fluxes, which suffer from the drawback of perturbing the melt pool.

The double nozzle described in EP 0600250 supplies argon in an outer nozzle at a higher pressure than helium in the centre nozzle. Thereby, a depression is achieved. The objective of this invention was to widen the keyhole by depression of pressure to increase the coupling of the laser beam. This is only advantageous in CO_2 laser welding and does not seem to be applied in production at all.

Hermann, the inventor of EP 0600250, mapped out all commercially available gas nozzles [HERMANN 2004]. He concludes, "up to now *no* coaxial gas nozzle system is on the market guaranteeing a pure process gas atmosphere at the fusion melt zone".

5.1.3 Cross-jets

The laser beam propagates through the nozzle towards the workpiece. Fumes and spatter originating from the welding process move in the opposite direction. Optical components, such as focusing lenses, are very sensitive with regards to contamination by fumes and spatter. These contaminations obstruct the beam and lead to degradation of its optical properties by refraction. The energy of the beam can be released in the optical systems by such contaminations initiating damage or even destruction by over-heating. Thus, even if the optical components are separated from direct contamination by a protection glass, the contamination must be removed before reaching the optical components in order to prevent obstruction. For lateral nozzle systems the state-of-the-art remedy was a cross-jet of pressurized air rejecting particle contaminations such as fumes and spatter from the focusing lens or the protection glass. Such cross-jets were researched as to improve the air knife they generate by fluid dynamically advantageous design of their emerging unit. The best design of the emerging unit is a rectangular slit geometry instead of a line of circular Laval nozzles. A combination of such cross-jets together with a coaxial nozzle constitutes the 'integrated nozzle', shown in figure 5.1 c). This design is the most advanced design of a coaxial nozzle integrating a cross-jet to protect the optical components.

This 'integrated nozzle' patented by Fraunhofer ILT Aachen is made up of a coaxial double conic nozzle supplying the process gas through the outer nozzle, whereas the centre nozzle is void of process gas [MAIER 1999, p. 62].

The process gas is directed to the fusion zone at an angle, which is detrimental to the prevention of process pores. The cross-jet is located right above the centre nozzle. Kern showed by Schlieren optic technique that the process gas in a coaxial nozzle experiences suction towards the cross-jet. Thus, the process gas is removed from the fusion zone [KERN 1999, p. 29]. The 'integrated nozzle' does not prevent the admixture of air into the centre nozzle. Thus, expensive process

6 Synergies of Bifocal Hybrid Laser Welding

6.1 Introduction to synergies in laser beam welding

This chapter gives an account of synergies in BHLW as compared to its constituent processes, i.e. keyhole welding by an Nd:YAG laser and CMW by an HPDL, in comparison to other state-of-the-art laser beam welding techniques. For a synergy two propositions have to be fulfilled:

1. Two or more processes interact such that their combined effect is greater than the *sum* of their individual effects.
2. The behaviour of the whole system is not predictable from the behaviour of its separate parts.

The first proposition requires *quantitative* analysis of each of the contributing processes as a prerequisite to demonstrate a synergy according to this definition. Although individual processes *act in* the same process zone, as e.g. in laser augmented MIG welding, they do not nonetheless not synergistically interact if their superpositioned effect *equals* the sum of their respective contributions. The second proposition calls for *theoretical* analysis, as one can only speak of a synergy if experimental results well surpass what could be induced and expected form experimental data already known. Process or system technology advantages of BHLW are not treated in this chapter, because mere advantages do not satisfy these propositions to be termed synergy. These advantages, which are especially important for production engineering, are dealt with in the next chapter.

6.2 Increase of welding efficiency

Superior process efficiency manifests itself in an increase of the correlated parameters, e.g. welding speed or penetration depth. The synergies of BHLW are demonstrated by presentation of direct measurements of the energy input efficiency η_{EI} and melting efficiency η_M. In the literature there are definitions of ‘process efficiency’ and ‘melting efficiency’ in terms of the power of the laser employed [LANDOLT-BÖRNSTEIN 2004, p.62; HÜGEL 1992, p. 245]. Others resort to the energies released and introduce the ‘energy transfer efficiency’ as a further figure of merit [FUERSCHBACH 1996]. In this dissertation the following terminology and definitions are adopted: The energy input efficiency η_{EI} is the ratio of the radiation energy emitted by the laser and the energy released as heat within the workpiece. The melting efficiency η_M is the ratio of the energy released as heat within the workpiece and the amount of energy for melting a part of the workpiece, i.e. the total enthalpy of melting to create the seam.

It should be noted that this definition of melting efficiency is different form that encountered in the literature [LANDOLT-BÖRNSTEIN 2004]. The definition of melting efficiency adopted in this dissertation is necessary to establish the results presented in this paragraph. Although it is potentially confusing to reuse the term melting efficiency in the context of this dissertation, this could not be avoided for lack of an alternative apt term. This dissertation is free to adopt any terminology as it pleases.To measure these figures of merit, η_{EI} and η_M, a new experiment was designed. The power of the laser and the energy absorbed within the workpiece were determined by a calorimetric measurement. The experiment was conducted in a calorimeter, which was designed like a chamber and was filled with process gas during the experiment. For the measurement the reference alloy EN AW-6060 and argon as process gas was used. The welding speed corresponded to 4 m min^{-1}.

For the HPDL η_{EI} was experimentally determined to be 35.6% with a standard deviation of 2.5%. This value of η_{EI} is higher as the absorptivity of aluminium, which is 0.13 for the centre wavelengths of the HPDL, would seem to allow for. The Nd:YAG laser emitting 3 kW gave a mean energy per unit length of the seams of 262.5 Joule cm^{-1} with a standard deviation of 32.9 J cm^{-1}. This corresponds to a standard error in the mean of 14.7%. For the 3 kW-HPDL the mean energy per unit length is 129.8 Joule cm^{-1} with a standard deviation of 32.9 Joule cm^{-1}. For BHLW at 6 kW, i.e. the Nd:YAG and the HPDL are equally emitting their maximum output power of 3 kW, the experimental value is 389.8 Joule cm^{-1} with a standard deviation of 26.3 Joule cm^{-1}.

For the Nd:YAG laser η_{EI} is 65% with a standard deviation of 9.2%. This greatly surpasses the absorbtivity of aluminium, which is 0.07 for the wavelength of the Nd:YAG laser. Multiple reflections on the wall within the keyhole can account for this result. The *theoretical* combination (i.e. purely mathematical by calculating the weighted arithmetic mean) of these figures of η_{EI} renders a nominal value for η_{EI} of 50.3% for BHLW. It should be noted that the *measured* value of η_{EI} for BHLW is 48% with a standard deviation of 1.99% and a standard error in the mean of 0.9%. The theoretical value of η_{EI} agrees with the measured value within the limits of experimental error. These measurements show that for η_{EI} no synergy could be found according to proposition 1 in paragraph 6.1.

The melting efficiency η_M of Nd:YAG laser welding is 12.6% with a standard deviation of 1.3%. For the HPDL it is 3.5% with a standard deviation of 0.7%. The *mathematical* combination (again by calculating the weighted arithmetic mean) of those values suggests a *theoretically* expected value for the hybrid process of both lasers of 8.05%. In the experiment η_M of BHLW was found to be 15.2% with a notably small standard deviation of 0.048%. This corresponds *nearly* to a **doubling** of melting or process efficiency. This clearly indicates a true synergy of BHLW, because the beam quality of the HPDL is up to two orders of magnitude inferior to that of the Nd:YAG laser. Additionally, this elucidates the *nature* of the synergy as well. The HPDL does not affect the energy input of the Nd:YAG laser. Instead, the *creation* of melt is synergistically enhanced.

The *doubling* of the melting efficiency is a very significant result for industrial production. This can be proven by virtue of the speeds of welding: Unsurprisingly, the speed of welding still enabling root fusion rises from the benchmark speed set by the Nd:YAG laser of around $2 \div 3\ \mathrm{m\ min^{-1}}$ to $5.5\ \mathrm{m\ min^{-1}}$ in BHLW, i.e. the speed of welding is nearly doubled. This is in agreement with this measurement of melting efficiency. As described above, the melting efficiency nearly doubled as well. The melting efficiency η_M is connected to the Rykalin number Ry

The melting efficiency η_M is connected to the Rykalin number Ry according the Fuerschbach's definition: [FUERSCHBACH 1996]:

$$Ry = \frac{E_a \cdot v_w}{\alpha^2 \Delta H_m} \qquad \text{(Equation 6.1)}$$

E_a is the energy absorbed by the workpiece, α is the thermal diffusivity of the workpiece at the liquidus temperature, ΔH_m the enthalpy of melting. Although Ry predicts a rise of melting efficiency upon increasing v_w, the doubling of η_M observed for the BHLW system must be a synergetic effect.

This result can also be more easily appreciated by an experiment of mind: The maximum welding speed of a 3-kW Nd:YAG laser to guarantee root fusion in the reference specimen laser is $2 \div 3\ \mathrm{m\ min^{-1}}$. If one wanted to approximately double this welding speed, an Nd:YAG laser of 6 kW output power would be necessary. However, in the case of BHLW just an HPDL of 3 kW output power was used. The HPDL emitting 3 kW could *not* create a proper weld in the reference specimen, since the energy input efficiency and melting efficiency of this HPDL are much lower than those of the Nd:YAG laser. However, teaming up those two laser sources in BHLW enables a synergistic result, which could not be predicted from combining those two lasers in *mind*. This experiment of mind will be explained more carefully in the following.

The assessment of welding techniques for industrial applications is normally centred on welding speed. An increase of welding speed allows reducing cycle times. Reduced cycle times translate to cost reductions per unit by improved productivity. As explained in paragraph 4.1 CMW by the HPDL could not create stable welds in aluminium. Beyond a certain threshold in HPDL welding an increase of HPDL power does not lead to deeper penetration but only to a broadening of the seam width (c.f. figure 6.1).

Figure 6.1: Width of the weld seam versus velocity of welding and power of the HPDL

Figure 6.2: Depth of the weld seam versus laser powers in BHLW

Welding solely by an Nd:YAG laser enables a maximum speed for the reference specimen of approximately 2 to about 3 m min^{-1}. However, the quality of such welds is inferior, and root fusion cannot be guaranteed due to variations of the welding depth. For welding at a constant velocity of 4 m min^{-1} the variation of depth dependent on the individual powers of the two laser sources is shown in figure 6.2.

The maximum speed for robust welding without solidification cracking is v_w = 5.5 m min^{-1}, as is shown in detail in paragraph 8.2. Such seams exhibit robust root fusion without variation of depth and no porosity. The weld easily satisfies all requirements of quality group B as standardized in DIN EN ISO 13919-2. 6 kW-BHLW allows for more than doubling of the speed of welding although the 3 kW-HPDL alone could not generate satisfactory welds. The BPP of the HPDL is by *one* order of magnitude inferior to that of the 3 kW-Nd:YAG laser employed in BHLW. This increase of welding speed could not be extrapolated and therefore constitutes a true synergy of BHLW.

BHLW was put to the test. An industrial application for paper machinery necessitated a weld in thick sheets to be liquid proof. No established laser welding technology could be found by the paper machinery company satisfying the requirements as to penetration depth and seam quality. To solve this problem the following alloys were considered in a study: EN AW-5083, EN AW-5754,

7 Advantages of Bifocal Hybrid Laser Welding

In this chapter the advantages of BHLW are outlined and discriminated against the synergies described in the previous chapter. This distinction between synergies and advantages is important to fully comprehend their nature. Any improvement might be termed as an advantage however small it might be. But only those advantages where the whole is more than the sum of its constituent parts should deservedly be called a synergy. This is specifically important as it seems common place to designate mere advantages of various welding techniques as synergies. The advantages of BHLW do not fall short of the synergies as far as their improvements of aluminium welding are concerned.

7.1 Robustness

In BHLW the increase of process robustness is tangible if the instabilities induced by the process gas supply system are excluded, since the gas is invasive with regards to the melt pool, as shown in chapter 4. A chamber, which was thoroughly rinsed and was therefore exclusively filled with process gas, was used for welding experiments with different laser sources. Such a chamber excludes all possible external sources of disturbance and allows studying the robustness of the welding technique *for itself*.

The beads in the following figures 7.1 to 7.3 were all made in such a sealed gas chamber. HPDL and Nd:YAG laser welding are each considered on their own. In figure 7.3 the result of their combination in BHLW is shown for comparison.

Figure 7.1: *Top surface photograph of HPDL welding; seam is bent because the gas chamber did not permit a linear seam; chamber was filled with argon;* $P_{HPDL} = 3$ *kW;* $v_w = 4$ *m min*$^{-1}$*; bead on plate; EN AW-6060; angle* $\varphi = 6°$

The HPDL does not penetrate the specimen to a great depth. The surface was melted by CMW, as can be seen in figure 7.1.

Figure 7.2: *Top surface photograph of Nd:YAG laser welding; seam is bent because the gas chamber did not permit a linear seam; chamber was filled with argon;* $P_{Nd:YAG} = 3$ *kW;* $v_w = 4$ *m min*$^{-1}$*; bead on plate; EN AW-6060; angle* $\varphi = 6°$

The seam generated by the Nd:YAG laser is a deep penetration weld by virtue of a keyhole. The instabilities in Nd:YAG laser welding are obvious. Instabilities arose although a gas supply system was absent and the seam was produced in the gas chamber.

Figure 7.3: Top surface photograph of BHLW; seam is bent because the gas chamber did not permit a linear seam; chamber was filled with argon; $P_{BHLW} = 3$ kW + 3 kW; $v_w = 9$ m min^{-1}; bead on plate; EN AW-6060; angle $\varphi = 6°$

BHLW seams were produced at a normalized energy per unit length. The speed of welding had to be doubled for normalization, because the two lasers used emitted each 3 kW. As can be clearly seen in figure 7.3, the seam is free of instabilities proving the robustness of BHLW in *itself*.

It should be noted that in some cases it is a major challenge to guarantee process robustness for comparably *low* speeds of welding. Even thin sheets can be welded to high seam quality by accordingly reducing the power of the HPDL and the Nd:YAG laser. For thin sheets the speed of welding with BHLW is *low* as compared to Nd:YAG laser welding. This is desirable as high speeds necessitate high accelerations of the kinematical systems moving the workpiece or the optic system. These motions lead to inaccuracies and strain the kinematics. A high welding speed inhibits the segmentation of seams or reorientation of the welding direction. For thin sheet welding with an Nd:YAG laser the power of the laser cannot be lowered beneath a certain threshold if deep penetration by keyhole welding is to be sustained. For BHLW this threshold can be lowered since the material is melted by the HPDL. The Nd:YAG laser subsequently needs less energy to induce vaporization, which is a prerequisite for keyhole welding. This demonstrates the robustness of BHLW.

7.2 Reduction of relative crack length

Aluminium alloys exhibit a propensity to cracking in fusion welding depending on the distribution of their alloying contents. The details of cracking and cracking susceptibility are dealt with in section 8.2.1. To *completely* counteract cracks in welds of the reference alloy EN AW-6060 filler material cannot be forgone. A standardized experiment needs to be conducted to assess the merits of a given laser welding technology to reduce the propensity to cracking. The experiment must be designed such that external influences are excluded from affecting the result. This would otherwise lead to systematic errors. The experimental chamber employed in the preceding paragraph 7.1 to generate the results displayed in figures 7.1 to 7.3 was used again. The speed of welding was kept constant at 4 m min^{-1}. The macrographs for Nd:YAG laser and BHLW are shown in figure 7.4.

Figure 7.4: Cross-section macrograph for $v_w = 4$ m min^{-1}; left: Nd:YAG laser welding; $P_{Nd:YAG} = 3$ kW; right: BHLW; $P_{BHLW} = 3$ kW + 3 kW; chamber was filled with argon; bead on plate; EN AW-6060; angle $\varphi = 6°$

As can be clearly seen by the naked eye the relative crack lengths are greatly reduced in BHLW in comparison to Nd:YAG laser welding. The mean energy per unit length is doubled in BHLW compared to Nd:YAG laser welding for the parameters in figure 7.4. BHLW exhibits an in-line "post-heating" effect, which is very difficult to achieve by other state-of-the-art laser welding technologies. The penetration depth of the HPDL is negligible as compared to the penetration of the Nd:YAG laser displayed in figure 7.1. The HPDL does not act at depth, but rather at the surface. The Nd:YAG laser induced a deep reaching crack, as can be seen left in figure 7.4. In BHLW the HPDL obviated this prominent crack, c.f. right macrograph of figure 7.4. Additionally, the lengths and breadths of the cracks are mitigated and the absolute number of cracks is reduced. In figure 7.5 magnifications of the macrographs of figure 7.4 are shown and typical breadths of cracks are measured. For this impartial, random selection of measurement point the absolute length L was found to be 23.7 µm in Nd:YAG laser welding and approximately 8 µm in BHLW.

Figure 7.5: Magnification of cross-section macrographs of figure 7.4 for $v_w = 4\ m\ min^{-1}$*; left: Nd:YAG laser welding,* $P_{Nd:YAG} = 3\ kW$*; right: BHLW;* $P_{BHLW} = 3\ kW + 3\ kW$*; chamber was filled with argon; bead on plate; EN AW-6060; angle* $\varphi = 6°$

The *mere* reduction of relative crack lengths in BHLW as compared to Nd:YAG laser welding is important for production engineering, since one can suspect that the amount of filler material necessary to *completely* prevent cracking is reduced in BHLW as compared to classical Nd:YAG laser welding. In a laser production process the filler wire needs to be melted on the expense of the laser's capacity to melt the material. Thereby the necessity to dilute more filler material per unit time decreases the process efficiency of the *welding* process, since in laser welding it is the amount of base material melted which contributes to the process efficiency and not the amount of molten filler material as in classical GMAW processes. The problems encountered in the system technology to feed filler to the melt pool and how to forecast the filler supply rate for a given welding process is dealt with in paragraph 8.2.

The final upshot of this section is the reduction of crack propensity in BHLW as compared to Nd:YAG laser welding, which allows decreasing the dilution ratio. Dilution is dealt with in paragraph 8.2.

8 System Technology

8.1 Laser optic system

8.1.1 Experimental optic setup

An experimental setup was assembled to investigate the fundamentals of the combination of HPDL and Nd:YAG laser. The HPDL stack was directly integrated into the optical head. Its beam passes through a dichroic mirror orientated at an angle of 45° with respect to the beam's direction of propagation. The coating of the mirror transmits the radiation of the HPDL to a very high degree. The Nd:YAG laser beam is guided to the optical head via a fibreoptic cable, in which its beam is enlarged by a water-cooled collimator to a diameter of 44 mm. The beam is subsequently deflected by 90° with regards to the direction of propagation of the HPDL and is reflected at the bottom surface of the dichroic mirror. The Nd:YAG laser radiation is deflected into the beam path of the HPDL such that both beams are propagating parallel to each other. Both beams are focused by a spherical lens of f = 150 mm. Before the rays impinge on the workpiece they transgress the filter glass that protects the lens from spatter. Subseqently, they propagate coaxially within a gas nozzle. The experimental optical head is shown in figure 8.1.

All the welding results presented herein were generated with this experimental optical head. A number of drawbacks became obvious during operation of the experimental head. These drawbacks are forgone in the prototype optic system, which is consequently ready for industrial applications.

In the experimental optic setup the share of radiation of both lasers, which is not deflected towards the lens, falls onto a black anodized water-cooled beam trap. Thereby, heating up of the head is prevented. In practice, the sum of radiation power of 6 kW emitted by both lasers heated up the optic, since a fraction of the laser power impinged on the mount. This is the reason that the length of a continuous weld seam was limited to about 20 cm. Otherwise, the beam trap overheated and time had to be allowed for it to cool down. The gimbal mount of the dichroic mirror utilized four screws which did not permit a repeatedly accurate and retrievable adjustment of the dichroic mirror. Moreover, the rotational axes of the mirror mount were unsupported. This lead to a complicated and time consuming routine for varying the relative focal positions of the two beams. Reflections of radiation from the workpiece could re-enter the HPDL stack via the optical components. This radiation burned into the diodes of the HPDL resulting in a gradual reduction of output power of the HPDL stack. Particle and thermal emissions from the welding process did affect the experimental setup. Particles degraded the lenses and process radiation heated up the cavity, as the outer walls were blackened and therefore highly absorbent.

Figure 8.1: Experimental setup of the optical head; left: HPDL stack integrated into the head; right: headlong elevation of the experimental optic setup

The filler wire tube batch and the deflecting optic for the Nd:YAG laser are located on the same side of the HPDL. The wire could only be fed by torsion of the batch to the plane of longitudinal motion, as the plane itself was occupied by the Nd:YAG laser optic. The optic system is not mirror symmetric with respect to the direction of motion. This reduces accessibility and makes welding of T-joint geometries of extended parts impossible.

8.1.2 Optical engineering of the beam path

The beam path of the experimental optical setup was modelled by optical engineering software. All indispensable optical components and constraints were encoded and allowed abstract planning and optimization of the beam path and the optical components. All practical possibilities were evaluated. The final result of the components' arrangement is shown in figure 8.2.

Figure 8.2: Sequence of optical components of the optimized optical beam path

The encoding of the specific optical components revealed several shortcomings of the mirrors and lenses used in the experimental setup. It turned out that the experimental optic setup's *diffraction limit* is set by the apertures of the dichroic mirror and the focusing lens, as shown in figure 8.3. The footprint in figure 8.3 shows the image of the HPDL emerging after the experimental optic setup.

The objective was to design the optical components such that the optic is diffraction limited by the apertures of the optical components. The Rimray aberration plot (RIM) shows the magnitude of spherical aberration on the ordinate, whereas the abscissa renders the position of the rays in the aperture on entry of the optical system. Refraction is not accounted for by the RIM. The line spread function (LSF) gives the intensity distribution of the beam within the focal spot. Refraction and all wavelengths according to their individual weight are accounted for. The LSF shows the one-dimensional distribution of the intensity along the x-axis defined horizontally and transverse to the direction of propagation. The RIM and LSF for the HPDL and the Nd:YAG laser are displayed in figures 8.4 and 8.5 respectively.

Figure 8.3: Top: elevation of beam path; middle: aperture represented by the gimbal mount of the dichroic mirror; bottom: footprint-analysis of the resultant trimmed rectangular beam of the HPDL emerging after the experimental optical setup

The LSF can therefore be used to determine refraction effects and secondary maxima. A new dichroic mirror was designed accordingly. The fibre optic systems of the two lasers are standard components of the lasers’ manufacturers and had therefore to be accepted as the diffraction limit of the prototype optic.

Figure 8.4: Rimray aberration plot of both lasers employed in BHLW; top: HPDL according to dominant wavelengths; bottom: Nd:YAG laser for its single wavelength

9 Economic Case

In the proverbial chapter on the economic case, its authors facilely demonstrate the case by reliance on reduced unit costs. These calculations are normally based on assumptions which make them at best idealized or at worst fatally flawed. Each individual case has its own applications and needs, meaning that each one has unique circumstances and financial constraints. In current industry, dependant as it is on welders to apply hand-held techniques, difficulties in staffing make reaching production goals difficult. Welders are exposed to noxious emissions, which necessitate sophisticated equipment to satisfy health and occupational safety standards. Welding is regarded as heavy labour, and recruitment suffers from a shortage of applicants [MIKLOS 2004; BRAT 2006].

For reasons of laser safety and process velocities, laser beam welding is normally accomplished by standard kinematics such as robots or machining centres. Resistance spot welding has traditionally been applied by robots in the automotive industry. However, in ship and aircraft building, automation regarding welding has not taken place to a high degree as batch sizes are very small. In small-sized businesses hand-held welding is prevalent. This is not about to change – in handicraft enterprises the investment for laser sources is normally too high to amortise. Nonetheless attempts for hand-held laser welding systems have been made. It is dubious that they have conformed to laser safety standards. Whereas classical arc welding technologies cannot be automated, as they require a welder for good quality, laser welding is capable of being readily automated. Thus, laser safety standards do not only *necessitate* automation, but laser welding is *appropriate* for automation.

In small and medium-sized businesses (SMB) the application of robots and machining centres is increasing. Thus, laser welding applications can be readily adapted. In vehicle production enterprises laser welding applications are commonplace. Clearly then, the circumstances dictate whether a robot is needed. One suitable for welding costs approximately € 35.000.

Industrial experts are welcome to make their own cost estimates based on the following economic vertices of BHLW. The market launch of novel laser sources, such as fibre laser and HPDL of up to 10 kW output power, will substantially effect the prices of other high power cw-lasers such as Nd:YAG and CO_2 lasers. For BHLW, a conventional lamp pumped 3 kW-Nd:YAG laser was used for which one kilowatt of laser power cost approximately € 100.000. One

11 Conclusion

This dissertation has presented the process innovation of BHLW. While researching the fundamentals of LBW of aluminium, it became obvious that most state-of-the-art empirical process models suffered from seeming antinomies which ultimately could not be reconciled with the experimental evidence. This evidence was often documented in the literature with a paucity that forbade comparison. This necessitated benchmark studies under *ceteris paribus* conditions. This dissertation endeavours to state fully the process parameters needed to compare different process technologies. To do so, the merit of process efficiency specifically is the focus when comparing the various processes. Even the best wall-plug efficiency of the laser systems employed does not make up for reduced process efficiency. Thus, a new the welding efficiency was measured by a calorimetric measurement. The results allowed the accounting for the synergies of BHLW. In order to do justice to matters only those results have been called a

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13 Appendices

Appendix A: Derivation of the filler dilution formula (FDF)

Magnitudes given or regarded as constants during the welding process:

v_w	velocity of welding
v_f	velocity of the filler wire
P_L	power emitted by the laser
A_f	cross-sectional area of the filler wire
d_f	diameter of the filler wire
c_f	silicon content of the filler wire (for Al 4047 A the Si content is 12%)
c_b	silicon content in the base alloy (for EN-AW6060 the Si content is 0.5%)

Magnitude measured:

The cross-sectional area of the fusion zone A needs to be determined form cross-sections macrographs:

$$A = f(v_w, P_L)$$

The Si content in the fusion zone represents the desired magnitude c_{fz}, i.e. the dilution in the fusion zone. This dilution depends on the filler wire dilution. The determination of the FDF proceeds as follows:

$$V = V_f + V_b \qquad \text{(Equation 11.1)}$$

where V is the volume of the fusion zone, V_f the volume of filler wire, and V_b the volume of the base metal per unit time t.

$$V = A \cdot v_w \cdot t \qquad \text{(Equation 11.2)}$$

$$V_f = A_f \cdot v_f \cdot t = \frac{\pi \cdot d_f^2}{4} \cdot v_f \cdot t \qquad \text{(Equation 11.3)}$$

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