ND/YAG LASER-ASSISTED ARC WELDING
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Nd/YAG laser-assisted arc welding

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# CONTENTS

1. General introduction  
   1.1. Development of the hybrid laser-assisted welding system  
   1.2. Principles of arc welding and laser beam welding  
   1.3. Scope of the thesis  
   References  

2. Plasma plume generation and melting by low-power Nd/YAG laser  
   2.1. Introduction  
   2.2. Experimental  
   2.3. Results and discussion  
      2.3.1. Plasma plume generation  
      2.3.2. Measurement of the weld bead profile  
      2.3.3. Influence of shielding gas  
      2.3.4. Influence of power density  
      2.3.5. Influence of travel speed  
      2.3.6. Influence of laser power  
      2.3.7. Heat transfer  
   2.4. Conclusions  
   References
3. Influence of laser radiation on arc ignition

3.1. Introduction

3.2. Experimental set-up

3.3. Experimental results

3.3.1. General features of the laser-induced plasma plume

3.3.2. Measurements at electrode positive (EP)

3.3.3. Measurements at electrode negative (EN)

3.3.4. Influence of electrode distance on breakdown voltage

3.3.5. Influence of laser energy density on breakdown voltage

3.3.6. Influence of shielding gas on breakdown voltage

3.4. Discussion

3.5. Conclusions

References

4. Influence of laser radiation on welding arc stability

4.1. Introduction

4.2. Experimental

4.3. Results and discussion

4.3.1. Influence of laser radiation on arc stability

4.3.2. Stabilisation mechanism

4.3.3. Direct heating of plasma by laser beam

4.3.4. Spectroscopic measurements of the change in particle composition

4.4. Conclusions

References
5. Arc manipulation by means of a laser beam

5.1. Introduction
5.2. Experimental procedure
5.3. Results and discussion
  5.3.1. Manipulation of arc root position by a laser beam
  5.3.2. Current redistribution within the arc
  5.3.3. Applications
5.4. Conclusions
References

6. Welding efficiency of laser-assisted arc welding

6.1. Introduction
6.2. Experimental
6.3. Results and discussion
  6.3.1. Energy transfer efficiency
  6.3.2. Melting efficiency
  6.3.3. Analytical calculations
  6.3.4. Influence of torch position on the melting rate
6.4. Conclusions
References

7. Thermal and microstructural characteristics of laser-assisted arc welding

7.1. Introduction
7.2. Experimental set-up
7.3. FEM calculation of the thermal cycle
7.4. Results and discussion
7.4.1. Thermal behaviour 117
7.4.2. Weld bead profile 119
7.4.3. Weld microstructure 121
7.4.4. Phase transformation 125
7.5. Conclusions 129
References 131

Summary 133
Samenvatting 137
Acknowledgements 141
Curriculum Vitae 143
GENERAL INTRODUCTION

1.1 DEVELOPMENT OF THE HYBRID LASER-ARC WELDING SYSTEM

The welding world is continuously stimulating the exploration of new welding methods. This resulted in the development of a number of welding processes, such as arc welding, resistance welding, gas welding, electron beam welding and laser welding, etc [1.1, 1.2]. Of these processes arc welding is the oldest and up to now still the most important one for the metals industry.

Arc welding has evolved over time into different branches: shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), submerged arc welding (SAW) and plasma arc welding.
(PAW). Each of these processes has its own specific features and all are widely applied in industry today.

The newest weapon in the welding world is the laser beam. After the introduction of the high-power laser beam into the welding market, the laser welding activities grew quickly and now are taking over an increasing part of the welding work. Compared with conventional arc welding, the laser welding method has a very attractive aspect: the high-power density focused in the small laser spot can produce a much narrower weld bead. The weld thus has a high depth/width ratio and a small heat-affected zone, which consequently leads to less residual stress and deformation after welding [1.2-1.4]. However, these benefits have to live together with a few strong drawbacks: the equipment of the high-power laser is expensive and the running cost of laser welding is high due to the extremely low electric power – laser conversion efficiency and the strict accuracy requirements of the workpiece preparation.

At the end of the 1970s the idea appeared in the welding field that it might be advantageous to combine the laser beam with the arc to form a new welding method: hybrid laser-arc welding [1.5]. The expectations were to maintain the advantages and to avoid or reduce the drawbacks of the individual welding processes by their combination. The idea immediately drew the attention of researchers and later on caused a huge echo in the welding world.

Like in the case of any other new welding method, a proper and optimal use of the system requires a thorough understanding of it. The last 20 years have been the years of new experiments and new discoveries of the hybrid system. It appears that the most suitable arc welding process for the arc-laser combination is GTAW, GMAW or PAW. The laser beam applied in the hybrid system includes both the CO₂ laser and the Nd/YAG laser with either a continuous or a pulsed waveform. The power level of the laser beam varies from a few hundred to several thousand watts [1.5-1.16].
Not surprisingly, the results obtained with the different laser-arc combinations are far from uniform. Nevertheless, there is general agreement that the electric arc and the laser beam in combination behave no longer in the same way as they do under separate welding conditions. It also appears that the welding quality and efficiency can be improved by tuning to the optimal situation. Unfortunately, however, a clear and complete insight in the laser-arc interaction is lacking at present and many proposed explanations require further theoretical and experimental confirmation [1.5-1.16].

1.2 PRINCIPLES OF ARC WELDING AND LASER BEAM WELDING

Before presenting the scope of this thesis on the subject of laser-assisted arc welding, it is necessary to briefly introduce the basic principles of the individual arc welding and laser welding processes.

Taking direct current electrode negative (DCEN) GTA welding as the representative variant of the arc welding process, the arc plasma burning between the tungsten electrode (cathode) and workpiece (anode) can be regarded as consisting of three parts: the cathode fall region, the column region and the anode fall region [1.2, 1.17].

In the cathode fall region, a thin sheath with a high electric potential is formed by the accumulation of positive ions around the electrode tip. By means of thermionic emission and field emission electrons are emitted from the electrode surface and accelerated by the sheath potential into the plasma column. At the same time, the electrode is heated to a high temperature by the bombarding ions and the heat from the hot plasma near the cathode.

In the case of the column region, electrical neutrality is reached and consequently there is a constant electric field (in the order of 1 V/mm). Many discussions have been devoted to the thermal state of the particles in the arc
column region and evidence tends to support that indeed the conditions for local thermal equilibrium (LTE) are fulfilled in a high current welding arc column core [1.18-1.20]. Thus, the properties of the arc column plasma can be calculated according to the LTE theory. This makes it possible to use the Boltzmann distribution for describing the population density of the excited states of every species, the Saha equation for describing the particle density as function of temperature and the Planck function for determining the blackbody radiation intensity [1.21-1.22].

The tasks of the anode fall region are to receive the electrons from the arc column and to provide the positive ions. The welding current level is believed to have a strong influence on the behaviour of the anode. In case of a low current, the arc anode is ‘anode jet dominated’. Under these conditions $T_e$ (the electron temperature) can be much higher than $T_i$ (the ion temperature) and a reversed electric field can be built up to speed up the ionisation [1.23-1.25]. In the case of a high current, the arc anode mode changes to ‘cathode jet dominated’, where $T_e$ is almost equal to $T_i$ and the anode fall may drop to zero [1.24-1.26]. The heat input of the anode (workpiece) is provided by the electrons (kinetic and potential energy) together with heat transfer from the plasma [1.17]. The electric arc therefore can be regarded as a surface heat source. The melting of the workpiece and the formation of the weld pool are dominated by heat conduction and are influenced by the fluid flow inside the weld pool.

The laser beam is a coherent light beam with a single frequency. Because of its purity, the laser beam can be focused into a small spot to achieve locally a high energy density. The absorption of the laser energy by the metal workpiece surface, however, is in general extremely low and is strongly related to the workpiece surface conditions and the wavelength of the laser light. For
example, the surface of aluminium and copper have a reflectivity coefficient as high as 98% for a CO\textsubscript{2} laser beam and 95% for a Nd/YAG laser beam [1.4, 1.27].

In the case of laser welding, two fundamental modes exist: the heat conduction mode and the keyhole mode [1.3, 1.4]. When the laser energy density is low, the beam energy is absorbed by the metal surface and the heat is conducted from the surface inwards, which forms a semi-circular weld pool. Under these conditions welding is regarded as operative in the heat conduction mode. When the laser beam energy density is increased to above a threshold level, the metal temperature in the laser spot increases sharply and strong evaporation starts to occur. The strong evaporation has a drilling effect and forms a hole along the beam direction inside the metal. Under these conditions, the laser beam energy is absorbed by multi-reflection inside the hole and the absorption of the laser beam energy by the metal can increase to above 80% [1.28]. The weld-cross sections that result from these two modes are shown schematically in Fig. 1.1.

The profile of the keyhole and the surrounding liquid flow depends on the evaporation, the liquid surface tension and the buoyancy force. Unfortunately, a good physical model of the keyhole is not yet available due to the large number of physical processes involved and the chaotic situation [1.3, 1.29, 1.30].

The metal vapour generated from the keyhole extends above the workpiece and forms a so-called plasma plume. This plume can absorb and scatter the laser beam, thus greatly affecting the results of the laser welding process. For example, in CO\textsubscript{2} laser welding the plume can reach a length of several centimetres and a temperature of 8000 °C. In most cases it is recommended to oppose the generation and growth of the plume as much as possible [1.31-1.32].
Fig. 1.1 Comparison of conduction (upper) and keyhole (lower) welding modes.

1.3 SCOPE OF THE THESIS

After launching of the high power Nd/YAG laser into the market in recent years, the Nd/YAG laser is gradually replacing the CO$_2$ laser due to its flexibility of beam delivery and its relatively high absorption efficiency. In the case of the hybrid laser-arc welding system, the use of the Nd/YAG laser instead of the CO$_2$ laser in the combination has a bright application potential. Up to now, however, this combination has received only limited attention.

The objective of the study presented in this thesis is to obtain fundamental understanding of the interaction between the Nd/YAG laser beam and the
Nd/YAG Laser-assisted Arc Welding

welding arc and to explore the possible industrial applications of this new hybrid welding system.

After a general introduction, the thesis continues with the study of the Nd/YAG laser-induced plasma plume and the weld bead generation (Chapter 2). The results obtained under standard conditions are presented and attention is given to the influence of the shielding gas, the workpiece material, the laser power and the energy density. The chapter is expected to lay the foundation for the laser-arc interaction as discussed in later chapters.

It appears that the Nd/YAG laser-induced plasma plume is distinctly different from the welding arc plasma. However, the experiments indicate that the plasma plume can be used to facilitate the ignition of the welding arc. In fact, laser-assisted arc ignition can be used to replace the short-circuiting or high-frequency ignition techniques. The results are presented in Chapter 3.

The interaction of the laser beam with the arc plasma is discussed in Chapters 4 and 5. In Chapter 4 the emphasis is on the examination of the influence of laser radiation on arc stability. An arc stabilisation mechanism is proposed and this mechanism is validated by measuring the laser beam absorption by the arc, and by spectroscopic detection of the plasma composition. In Chapter 5 the results of arc manipulation experiments by means of a laser beam are presented. The experiments prove that not only the geometrical position of the arc, but also the arc current distribution can be controlled by the laser radiation.

The welding efficiency of laser-assisted arc welding (LAW) is addressed in Chapter 6. The energy transfer rate as well as the melting rate of GTA welding, laser welding and laser-assisted arc welding are compared experimentally and theoretically.

Last but not the least, the thermal and microstructural characteristics of the new hybrid welding system are presented in Chapter 7. By comparing the
results of FEM calculations with the results of experimental work, the characteristics of the laser-assisted arc welding system with respect to bead profile and microstructure are shown.

A summary of the results is given at the end of the thesis.
REFERENCES


Full knowledge of the phenomena occurring during laser beam welding forms a solid basis for the study of the laser-arc welding combination. In this chapter, the results are presented of experiments, which were carried out to examine plasma plume generation and melting by a low-power Nd/YAG laser (continuous wave, max. 500 W). In addition, the influence of the shielding gas, the travel speed, the laser power level and the energy density in the laser spot on the behaviour of the plume and the weld pool are addressed. It was found that a threshold value of the laser power density exists, above which intensive, pulsed plasma plume generation occurs, leading to keyhole mode laser melting. Below this threshold a moderate and smooth plume is generated and melting is dominated by heat conduction.
2.1 INTRODUCTION

This thesis deals with the combination of a low-power Nd/YAG laser beam and a welding arc (laser-assisted arc welding). Knowledge of the individual laser beam and the welding arc forms a solid base for understanding their interaction and is the prerequisite for the study of this interaction.

It is well known that in the case of laser welding the properties of the laser beam and those of the material to be welded are the fundamental factors that govern the welding process. Specifically, the laser energy absorption by the material, the laser-induced plasma plume and the weld bead generation are of importance [2.1-2.3]. In a similar way, these factors play an essential role in the interaction between the laser and the electric arc in the case of laser-assisted arc welding.

In this chapter, plasma plume formation, heat transfer and weld bead generation by a low-power Nd/YAG laser are examined and discussed. In addition, attention is given to the influence of shielding gas, power density and travel speed.

2.2 EXPERIMENTAL

The experimental set-up used is presented schematically in Fig. 2.1 and consists essentially of a Nd/YAG laser (HAAS 506D, continuous wave and max. 500 W) in combination with a metal workpiece in the form of a plate with dimensions of 200×50×3 mm. The most important properties of the laser are listed in Table 2.1. The operation of the laser beam in the experiments is realised by a personal computer and an I/O interface card (LabVIEW card). The experiments consisted of bead-on-plate heating/melting under different process conditions and in each situation the properties of the plasma plume and the weld pool were examined. Mild steel Fe 360, stainless steel AISI 304 and
Nd/YAG laser-assisted arc welding

the aluminium alloy AA 5083 were used as typical workpiece materials. Photographic imaging and spectroscopic analysis were used to investigate the laser-induced plasma plume. Transverse cross-sections of each weld were prepared and examined by optical microscopy (Olympus BX60M).

![Diagram of Nd/YAG laser setup](image)

**Fig. 2.1** Schematic drawing of experimental set-up.

| Table 2.1 Properties of Nd/YAG laser beam. |
|-----------------|-----------------|
| **Wavelength**  | 1.06 µm         |
| **Power level** | maximum 500 W, continuous wave |
| **Beam quality**| 30 mm mrad (multimode) |
| **Lens A**      | focal length 200 mm |
|                 | minimum focal spot Ø 0.6 mm |
|                 | focal depth 3.6 mm |
| **Lens B**      | focal length 100 mm |
|                 | minimum focal spot Ø 0.3 mm |
|                 | focal depth 0.9 mm |
The standard experimental conditions used are listed in Table 2.2. In order to obtain more information about the laser-induced plasma plume, the spectrum of the plasma plume was analysed by means of a spectrometer (Plasma II, Perkin Elmer). The spectrometer has a 1 m focal length and is equipped with a PM detector (see Table 2.3). The spectroscopic measuring set-up is schematically shown in Fig. 2.2.

Table 2.2 Standard experimental conditions.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>500 W</td>
</tr>
<tr>
<td>Focus position</td>
<td>0 mm (focus on surface)</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>argon 12 l/min (nozzle diameter 8 mm)</td>
</tr>
<tr>
<td>Travel speed</td>
<td>8 mm/s</td>
</tr>
<tr>
<td>Lens</td>
<td>lens A (200 mm focal length)</td>
</tr>
<tr>
<td>Material</td>
<td>Fe 360, AISI 304 and aluminium alloy</td>
</tr>
<tr>
<td></td>
<td>AA 5083 plates (200x50x3 mm)</td>
</tr>
<tr>
<td>Laser incident angle</td>
<td>normal to workpiece</td>
</tr>
</tbody>
</table>

Table 2.3 Monochromator specifications.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>1 m</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.018 nm</td>
</tr>
<tr>
<td>Linear dispersion</td>
<td>0.527 nm/mm</td>
</tr>
<tr>
<td>Grating</td>
<td>1800 lines/mm</td>
</tr>
<tr>
<td>Machine broadening (width at half height)</td>
<td>13.5 pm</td>
</tr>
</tbody>
</table>
2.3 **RESULTS AND DISCUSSION**

2.3.1 **PLASMA PLUME GENERATION**

When a laser beam impinges on a workpiece surface, optical energy is absorbed by this surface. As a consequence the temperature increases and the workpiece starts to melt locally after which evaporation occurs. The metal vapour flows upwards from the workpiece surface due to the evaporation force and buoyancy forces, thus forming the so-called plasma plume. It appears that the formation and the properties of the plume depend on the properties of the workpiece, the laser beam and the ambient gas.
Chapter 2 Plasma Plume Generation and Melting by Laser

Under standard conditions, in the case of both stainless steel AISI 304 and mild steel Fe 360 strong plume generation is observed, whereas in the case of the aluminium alloy AA 5083 the beam power scarcely creates a visible plume. Photographic images of the plumes generated are shown in Fig. 2.3. The plume profiles deviate from normal due to the flow of the shielding gas.

Fig. 2.3 Photographic images of plasma plume under standard conditions in case of AISI 304 (left) and Fe 360 (right) as workpiece material. The plume profiles deviate from normal due to the flow of the shielding gas.

To obtain more insight in the properties of the plume, spectroscopic measurements on the plume generated in the case of a Fe 360 workpiece were performed. The results are listed in Table 2.4 and indicate that radiation with a wavelength of 385.6 nm is emitted due to electrons of iron atoms jumping from a low excitation level to the base energy level. Neither argon atom lines nor iron ion lines could be detected. The results indicate that the plume has a low temperature and a low ion/electron density. When comparing the obtained results with the results obtained by Lacroix et al. [2.4], it can be estimated that
the electron density in the plume under the present conditions is smaller than $10^{16} \text{ cm}^{-3}$.

Table 2.4 Results of spectroscopic measurements.

<table>
<thead>
<tr>
<th>Measured position (above surface)</th>
<th>Intensity of 385.6 nm line (arbitrary scale)</th>
<th>Line profile (width at half height)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 mm</td>
<td>1650</td>
<td>30 pm</td>
</tr>
<tr>
<td>2.5 mm</td>
<td>550</td>
<td>17.5 pm</td>
</tr>
<tr>
<td>4.5 mm</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

To demonstrate the presence of charged particles in the plasma plume, the plume was immersed in an electric field, produced by applying a voltage between a tungsten electrode (Ø2.4 mm, 50 degree tip angle) and the workpiece. The set-up used is shown schematically in Fig. 2.4.

Using this set-up the current between the electrode and the workpiece was measured as a function of time. The obtained results show that after a certain incubation time a small steady-state current starts to flow between the electrode and the workpiece. An example of the results is presented in Fig. 2.5. Although accurate particle densities are difficult to be obtained from the results, the measurements clearly indicate the presence of charge particles in the plume. Furthermore, it was found that the plume generation is rather continuous. More detailed information is presented in Chapter 3.
Fig 2.4 Charged particle measurement set-up.

Fig 2.5 Current as function of time (lens A, voltage 40 V, electrode positive).
2.3.2 MEASUREMENT OF THE WELD BEAD PROFILE

The weld bead profiles obtained from the transverse cross-sections show that in the case of AISI 304 and Fe 360, the molten zones are heat-conduction mode dominant, the depth/width ratio being about 0.25. However, the depression in the middle of the weld indicates that downward liquid flow also plays a role in the weld bead formation, which presumably is related with the recoil force caused by the evaporation. In the case of the aluminium alloy AA 5083, a small semi-spherical molten zone is produced, which is the typical shape produced by pure heat conduction. Transverse weld bead profiles of the steel welds are shown in Fig. 2.6.

Fig 2.6 Transverse cross-sections of welds in AISI 304 (above) and Fe 360 (below) obtained under standard conditions.
2.3.3 INFLUENCE OF SHIELDING GAS

When replacing argon as shielding gas by helium, the plume size reduces to around half of that in argon as shown in Fig. 2.7. This observation can be qualitatively explained by the fact that the heat conductivity of helium is much higher than that of argon [2.5], which causes the plume temperature in the case of helium as shielding gas to be much lower than in the case of argon as the shielding gas. As a consequence of this it should be expected that the radiation and thus the visible plume size is reduced. The fact that the ionisation and excitation energies of helium are much higher than those of argon only plays a minor role. Under the present conditions the ionisation and excitation of these inert atoms are negligibly small in comparison with those of the metal atoms present. The bead dimensions in the case of helium turned out to be not significantly different from those in the case of argon. These results indicate that the plume has a negligible influence on the beam thermal efficiency under the tested conditions.

Similar experiments were also conducted in open air. A noticeable increase of plume size and bead profile was found. The depth/width ratio of the bead cross-section is about 1 and the weld surface area is about twice as large as in the cases of argon and helium. It is believed that these effects are due to the oxide layer formed on the metal surface, which dramatically improves the radiation absorption rate. Plume images in argon, helium and open air in the case of workpiece AISI 304 are presented in Fig. 2.7. Weld bead cross-sections in AISI 304 under argon shielding, helium shielding and under open air are presented in Fig. 2.8.
Fig 2.7 Photographic images of laser-induced plasma plume: a) workpiece AISI 304 in argon, b) workpiece AISI 304 in helium and c) workpiece AISI 304 in open air.

Note that in figures a and b the plasma plume deviates from normal due to the flow of the shielding gas, whereas in figure c the plume extends vertically due to the absence of shielding gas flow.
2.3.4 INFLUENCE OF POWER DENSITY

Attempts were also made to determine the influence of the laser power density on the induced plasma plume and the weld bead. Increase of power density to $7 \times 10^5$ W/cm$^2$ was achieved by using a 100 mm focal length lens (instead of the 200 mm focal length lens used under standard conditions). It was found that with other conditions unchanged, increased evaporation occurs accompanied by spattering. As a result of this, the plume becomes stronger and irregular, while the weld bead becomes deeper. Plume image and weld cross-
sections in the case of welding with stainless steel AISI 304 as the workpiece are shown in Fig. 2.9.

![Photographic image of plume (above) and cross-section of weld in workpiece AISI 304 (below) when using a lens with 100 mm focal length.](image)

Fig 2.9 Photographic image of plume (above) and cross-section of weld in workpiece AISI 304 (below) when using a lens with 100 mm focal length.

Increase of the power density also has a significant effect on the number and distribution of charged particles in the plume, as reflected by the results of electrode probe measurements. Strong fluctuations in the current occur and the plume is now formed in an uncontinuous, pulsed way. Fast Fourier Transform
(FFT) frequency analysis of the current data indicates that the fluctuation has a peak frequency in the order of 1 kHz. It also appears that the plume is almost immediately generated when the laser is started, which is illustrated in the current-time plot of Fig. 2.10. The weld bead cross-section clearly shows the influence of the strong plume generation. The downward recoil force creates a high depth/width ratio of about 0.7. In fact a keyhole inside the material is produced as shown in Fig. 2.9.

![Current vs Time](image)

**Fig 2.10** Current as function of time (lens with 100 mm focal length, voltage 5 V, electrode positive).

In the case of the aluminium alloy AA 5083, the increased power density does not result in an increase of the laser energy absorption: no detectable plume is produced and the molten zone is negligibly small, even smaller than when using the 200 mm lens.

### 2.3.5 Influence of Travel Speed

To determine the influence of travel speed on the induced plasma plume and the weld bead, the travel speed was varied from 2 to 14 mm/s while
keeping the other parameters constant. The travel speed is a relevant parameter since it is directly related with the laser material processing time. It appears that the evaporation of steel only needs about a few milliseconds heating time of the metal surface when using the 200 mm lens, whereas the necessary heating time for evaporation is undetectably small in the case of the 100 mm lens. It was found indeed that the influence of the travel speed on the plume size is insignificant in the case of AISI 304 and Fe 360 within the range of the tested travel speed. However, the volume of the molten metal reflected by the bead cross-section becomes smaller with increasing travel speed. Figures 2.11 and 2.12 show the weld surface area and the depth/width ratio of the cross-section as function of travel speed for an AISI 304 workpiece.

Fig. 2.11 Weld surface area and depth/width ratio of transverse weld cross-section as function of travel speed using a lens with a 200 mm focal length (workpiece AISI 304).
Fig 2.12  Surface area and depth/width ratio of transverse weld cross-section as function of travel speed using a lens with a 100 mm focal length (workpiece AISI 304).

2.3.6 INFLUENCE OF LASER POWER

The influence of the laser power on the behaviour of plasma plume and weld pool was also examined. Experiments were conducted in the range of 100-500 W using AISI 304 and Fe 360 as workpiece material. It was found that the lowest power for visible plume generation for both steels under standard conditions is about 350 W for the 200 mm lens and 100 W for the 100 mm lens. With decreasing laser power, the weld bead dimensions decrease. The results obtained with the 100 mm lens and with AISI 304 as workpiece are shown in Fig. 2.13.
Fig 2.13 Surface area and depth/width ratio of transverse weld cross-section as function of laser power using a lens with a 100 mm focal length (workpiece AISI 304).

The above experimental results prove that the formation of the weld pool in the case of laser beam welding depends on the laser energy absorption rate per unit area. When this absorption rate exceeds a specific threshold value, intensive and pulsed evaporation occurs and the weld bead shows the characteristics of a downward force. Under these conditions the keyhole mode becomes operative. Below the threshold value, moderate and smooth evaporation occurs and heat conduction dominates the weld pool formation. This leads to a transverse cross-section with a small depth/width ratio. Under these conditions the heat conduction mode is dominant. The results of the experiments indicate that the threshold laser power level for intensive evaporation and keyhole formation under the standard conditions is $5.7 \times 10^5$ W/cm$^2$ for both stainless steel AISI 304 and mild steel Fe 360.
2.3.7 HEAT TRANSFER

It has been shown in the foregoing that when a laser beam hits the surface of a metallic workpiece, heat is transferred to the metal, the amount of heat depending on the wavelength and the power density of the laser radiation as well as the physical properties of the metal. It is appropriate to express this heat in terms of the so-called welding efficiency. The definition of welding efficiency includes the energy transfer efficiency $\eta_E$ and the melting efficiency $\eta_m$, as expressed in the following equations:

$$\eta_E = \frac{Q_i}{\int W dt}$$  \hspace{1cm} (2.1)

$$\eta_m = A \cdot v \cdot t \cdot (\int C_p dT + H_f)/Q_i$$ \hspace{1cm} (2.2)

where $Q_i$ is the energy absorbed by the workpiece, $W$ the laser power, $C_p$ the heat capacity of the workpiece, $A$ the area of the transverse weld cross-section, $v$ the travel speed, $T$ the temperature, $t$ the welding time and $H_f$ the latent heat of fusion of the workpiece material.

For the determination of the energy transfer efficiency $\eta_E$ and the melting efficiency $\eta_m$, it is necessary to measure the net heat input from the welding source to the workpiece and the transverse surface areas of the welds. A detailed description of the measuring methods can be found in Chapter 6.

The results of energy transfer measurements show that in the case of Fe 360 as the workpiece material about 56% of the laser energy is absorbed when using a 100 mm lens at 8 mm/s and argon as shielding gas. Based on measurement of the weld surface area and the enthalpy of the steel $1(1384 \text{ J/g})$ [2.6], the melting efficiency is calculated to be about 29%.
2.4 CONCLUSIONS

On the basis of the results presented in this chapter the following conclusions can be drawn.

1) When a laser beam impinges on a metal surface optical energy is absorbed, which locally leads to melting and evaporation of the metal. The evaporated metal is pushed upwards forming the so-called laser-induced plasma plume.

2) The laser energy density is characterised by a threshold value, below which a moderate and smooth plume and a semi-spherical weld bead are formed (heat-conduction mode); above this threshold value, intensive and pulsed evaporation occurs, resulting in a large plasma plume and a weld bead with a high depth/width ratio (key-hole mode).

3) The shielding gas has a significant influence on plume and bead formation. Helium as the shielding gas results in a plume about half the size of that of argon. In open air, the surface oxidation dramatically increases the laser energy absorption, which leads to an increase of plume size and weld bead area.

4) The influence of travel speed on plume generation is insignificant within the tested range. However, with increasing travel speed the weld pool volume decreases, whereas the weld bead depth/width ratio remains similar.

5) Experiments show that in the case of Fe 360 as workpiece material a 500 W Nd/YAG laser has a 56% energy transfer efficiency and a 29% melting efficiency at a travel speed of 8 mm/s and with argon as the shielding gas.
REFERENCES


INFLUENCE OF LASER RADIATION ON ARC IGNITION

This chapter deals with the possibilities of using the laser-induced plasma plume as a tool to facilitate the ignition of the welding arc. Experiments were carried out using a standard gas tungsten arc (GTA) welding set-up in combination with a low-power (max. 500 W) Nd/YAG laser. By means of this laser a plasma plume was created above the workpiece and the breakdown voltage for arc ignition was determined by measuring the transient current between the electrode and the workpiece as a function of voltage. It was found that the laser-induced plasma plume strongly reduces the breakdown voltage for ignition, its effect depending on electrode polarity, electrode-workpiece distance and shielding gas. The results obtained are discussed in terms of thermionic emission and field emission.
3.1 INTRODUCTION

As described in the previous chapter, laser energy is transferred to the metal when a laser beam is focused on a metal surface, which locally leads to a rapid increase of the metal temperature. If the laser energy density is sufficiently large, the metal will melt and eventually evaporate. In the latter case, the metal vapour is pushed upwards from the metal surface and in this way it forms the so-called laser-induced plasma plume.

Due to its large influence on the laser welding process, the laser-induced plasma plume has received extensive attention in the past [3.1-3.4]. It appears that the size and the properties of the plume depend strongly on the circumstances, particularly on the energy density of the laser beam, the physical properties of the metal and the physical properties of the ambient gas.

In gas tungsten arc welding (GTA welding), an electric arc burns between a tungsten electrode and the workpiece to be welded. The electric arc consists of a high temperature plasma (~ 5,000 – 20,000 K), which is separated from the electrodes by the anode fall region and the cathode fall region, respectively [3.5, 3.6]. Key element in the ignition of the arc is the emission of electrons by the cathode. This can be realised by local heating of the cathode to a sufficiently high temperature (thermionic emission) and/or by creating a high electric field in front of the cathode (field emission). The welding arc is normally ignited by short-circuiting or high-frequency methods, which is either laborious or creates detrimental electro-magnetic noise.

This chapter presents the results of a study dealing with a new approach of arc ignition, which makes use of the laser-induced plasma plume as a tool to facilitate the ignition of the welding arc.
3.2 EXPERIMENTAL SET-UP

The experiments were carried out using a standard GTA welding torch in combination with a HAAS 506D Nd-YAG laser (max. 500 W). The welding torch is placed vertically above an austenitic stainless steel workpiece (AISI 304 plate of 50×30×3 mm). The laser beam is inclined at 30 degree to normal and focuses on the workpiece surface right below the electrode. The electrode and workpiece are connected to a DC power source. The electric current in the electrode - workpiece circuit loop is monitored using a 1 MHz oscilloscope (Nicolet), which measures the transient voltage over a 1 Ω serial resistance.

The experiments were carried out with argon as shielding gas. To reduce the blowing away of the plasma plume by the shielding gas, a shielding cup (∅ 50 mm) was used, which surrounds the plume area. The experimental set-up is schematically illustrated in Fig. 3.1.

![Schematic illustration of experimental set-up.](image)

Fig. 3.1 Schematic illustration of experimental set-up.
The transient current through the electrode - workpiece loop was measured under various experimental conditions. The standard experimental conditions used are listed in Table 3.1.

Table 3.1  Standard experimental conditions.

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>stainless steel AISI 304 (50×30×3 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td>tungsten (2% Th), Ø 2.4 mm, 50 degree tip angle</td>
</tr>
<tr>
<td>Polarity</td>
<td>electrode negative (EN) or electrode positive (EP)</td>
</tr>
<tr>
<td>Electrode - workpiece distance</td>
<td>2 mm (EN) and 4 mm (EP)</td>
</tr>
<tr>
<td>Nd/YAG laser</td>
<td>500 W continuous wave</td>
</tr>
<tr>
<td></td>
<td>wave length 1.06 μm</td>
</tr>
<tr>
<td></td>
<td>incident angle 30 degree to normal</td>
</tr>
<tr>
<td></td>
<td>focus spot diameter 0.45 mm (3.15×10^5 W/cm²)</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>argon (2 l/min)</td>
</tr>
</tbody>
</table>

3.3  EXPERIMENTAL RESULTS

3.3.1  GENERAL FEATURES OF THE LASER-INDUCED PLASMA PLUME

It was found that under the experimental conditions applied, the laser beam generates a plasma plume just above the surface of the workpiece, the size and luminosity of the plume depending on the laser power and the shielding gas used. As discussed in Chapter 2 spectroscopic measurements reveal only one emission line with a wavelength of 385.6 nm, which is generated by the iron vapour present in the plasma plume. The intensity of this line depends on the
measuring position in the plume. No argon emission was observed. Although the obtained results do not allow drawing quantitative conclusions, it appears that the plasma plume generated under the experimental conditions has a relatively low temperature and, consequently, the degree of excitation is small (see Chapter 2).

3.3.2 MEASUREMENTS AT ELECTRODE POSITIVE (EP)

Experiments were first carried out under standard conditions with the electrode positive (the electrode is connected to the positive pole of the DC power source). As an example of the results obtained, Fig. 3.2 presents the current as function of time for different values of the voltage. It can be seen that at relatively low voltage (40 V) a current starts to flow between the electrode and the workpiece after a short incubation time, which rapidly reaches a steady state level in the order of a few mA (Fig. 3.2a). When the voltage is increased, the steady state current rises to an increasingly higher level (Fig. 3.2b). However, when the voltage exceeds a certain value, breakdown occurs: the current starts to rise exponentially, reaching a level determined by the power source (Fig. 3.2c). When using a welding power source, breakdown leads to arc ignition. By measuring the transient current as function of the applied voltage, the breakdown voltage was determined. In Fig. 3.3 the results obtained are summarised in a current versus voltage plot.
Fig. 3.2  Current as a function of time for different values of the voltage (electrode positive). Laser is triggered at 0 ms.  
a) $U = 40$; b) $U = 75$ V; c) $U = 85$ V.
Fig. 3.3 Steady state current as function of applied voltage (electrode positive).

3.3.3 MEASUREMENTS AT ELECTRODE NEGATIVE (EN)

Experiments were also carried out under standard conditions with the electrode negative (the electrode is connected to the negative pole of the DC power source). As an illustration of the results obtained, Fig. 3.4 shows the current as a function of time for three different values of the voltage. It can be seen that at a voltage of 80 V a small current flows between electrode and workpiece, which slightly increases with time and reaches a value in the order of a few hundred μA (Fig. 3.4a). When the voltage is increased, the saturation current level slightly increases and irregular current peaks (sparks) start to appear in the current-time oscillogram (Fig. 3.4b). When further increasing the voltage, the sparks rapidly increase in number and magnitude and eventually
develop into electric breakdown and arc ignition (Fig. 3.4c). In Fig. 3.5 the results obtained are summarised in a current versus voltage plot.

![Graph a)](image1)

![Graph b)](image2)

![Graph c)](image3)

Fig. 3.4  Current as a function of time for different values of the voltage (electrode negative). Laser is triggered at 0 ms.
 a) $U = 80$ V; b) $U = 100$ V; c) $U = 110$ V.
3.3.4 INFLUENCE OF ELECTRODE DISTANCE ON BREAKDOWN VOLTAGE

Following the procedure described above, the breakdown voltage was determined for different values of the distance between the electrode and the workpiece both under electrode positive and under electrode negative conditions, the other parameters being kept at their standard value. The results are plotted in Fig. 3.6. For comparison, the breakdown voltage without laser radiation under the same conditions is also given in the figure.

It can be seen that both in the case of electrode negative and in the case of electrode positive the breakdown voltage increases with increasing distance. This is expected, because in order to maintain the same electric field between the electrode and the workpiece a higher voltage is needed when increasing the electrode-workpiece distance.
Fig. 3.6 Breakdown voltage as a function of electrode distance.

It can also be seen in Fig. 3.6 that the breakdown voltage under electrode positive conditions is somewhat smaller than under electrode negative conditions, whereas the breakdown voltage under both conditions is much smaller (by about a factor 20) than that without laser radiation. The cause of this behaviour will be addressed in section 3.4.

3.3.5 INFLUENCE OF LASER ENERGY DENSITY ON BREAKDOWN VOLTAGE

The breakdown voltage was also determined for different values of the laser beam energy density. This was done by using different lenses providing different energy densities (see Table 3.2) while keeping the laser output energy at 500 W. The measured values of the breakdown voltage under electrode
positive and electrode negative conditions using the three different lenses are plotted versus electrode distance in Figs. 3.7 and 3.8.

Table 3.2 Laser beam power density of different lenses.

<table>
<thead>
<tr>
<th>Focal spot (mm)</th>
<th>Focal length (mm)</th>
<th>Power density ( \times 10^5 , \text{W/cm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>100</td>
<td>7.08</td>
</tr>
<tr>
<td>0.45</td>
<td>150</td>
<td>3.15</td>
</tr>
<tr>
<td>0.60</td>
<td>200</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Fig. 3.7 Influence of laser energy density on the breakdown voltage (electrode negative).
Fig. 3.8 Influence of laser energy density on the breakdown voltage (electrode positive).

Surprisingly, the results show that the breakdown voltage increases with increasing laser energy density. In order to elucidate the underlying mechanism, the change in plume properties caused by the increased laser energy density was examined by carrying out additional experiments under electrode negative conditions, using a low potential (5 V) between the electrode and the workpiece and a large serial resistance (1.2 kΩ) in the circuit. Under these conditions the collision ionisation induced by the movement of the electrons in the external electric field becomes negligibly small and the current is a direct measure of the electron density in the plume. The results obtained in the experiments with the 0.3 mm and 0.6 mm lenses are presented in Figs. 3.9 and 3.10. The figures show that the number of electrons in the plume when using the 0.3 mm lens is several times larger than when using the 0.6 mm lens.
Fig. 3.9  Current versus time in the case of a lens with focal diameter 0.3 mm (voltage 5 V, electrode positive).

Fig. 3.10  Current versus time in the case of a lens with focal diameter 0.6 mm (voltage 5 V, electrode positive).

Accompanying the plume generation, a large noise is observed in the case of the 0.3 mm lens, which indicates that the pressure generated in the case of this lens is much higher than in the case of the 0.6 mm lens.

Furthermore, the shape of the molten weld pools formed using these two lenses was found to be different. In fact, the beginning of the keyhole mode development takes place in the case of the 0.3 mm lens by the vaporising force,
whereas a typical heat conduction mode is observed in the case of the 0.6 mm lens.

According to the gaseous ionisation theory, both the first and the secondary ionisation rate of a gas are functions of $E/p$ (where $E$ is the electric field strength and $p$ the gas pressure) [3.7]. More specifically, the theory predicts that the ionisation rate will have a lower value under higher pressure conditions. This implies that, although the initial number of electrons is higher in the case of the 0.3 mm lens than that in the case of the other two lenses, the collision ionisation (and thus the saturation current) will be smaller due to the pressure effect. This is illustrated in Figs. 3.11 and 3.12.

![Graph showing current versus time.](image)

Fig. 3.11 Current versus time in the case of a lens with focal diameter 0.3 mm (voltage 40V, electrode positive).

In the oscillogram of Fig. 3.9 it can be seen that in the case of the 0.3 mm lens, the current becomes highly fluctuating. The time interval between two current peaks is in the order of 100 μs. This high-frequency fluctuation obviously also hampers the current development.
Fig. 3.12 Current versus time in the case of a lens with focal diameter 0.6 mm (voltage 40V, electrode positive).

It was also found that the electrode surface was heavily contaminated by large spatter in the case of the 0.3 mm lens. The spatter contains metal oxide, which effectively reduces the electrode surface conductivity and leads to another cause for the higher breakdown voltage.

Experiments were also carried out to examine the influence of laser power on the breakdown voltage. Using the 0.3 mm lens and decreasing the laser power from 500 W to 100 W in step of 100 W, the current response as well as the breakdown voltage were measured. No specific relation was found between the breakdown voltage and the laser power. In case of the electrode positive and the laser power between 300 to 400 W, for example, the transient current grows to a higher level than in the case of 500 W laser power, whereas the breakdown voltage remains at a similar level. Furthermore, the results show a bad repeatability. This indicates that the breakdown situation becomes more delicate at decreased laser power, which makes more accurate experimental conditions and measuring tools necessary for further investigations.
3.3.6 INFLUENCE OF SHIELDING GAS ON BREAKDOWN VOLTAGE

To determine the influence of the shielding gas on the breakdown voltage, experiments were carried out under standard conditions both with argon and with helium as shielding gas. The results are plotted in Figs. 3.13 and 3.14 and show that the breakdown voltage in helium is considerably larger than that in argon, under electrode positive as well as under electrode negative conditions. This finding is directly related to the difference in heat conductivity of both gases. Since the heat conductivity of helium is higher than that of argon, the temperature of the plasma plume will be lower in helium than in argon. It might be expected that ionisation of the shielding gas also plays a role. The first ionisation energy of helium is 24.5 eV, whereas that of argon is 15.7 eV. It is obvious that the relatively low ionisation potential of argon favours the ionisation development in the plume. However, when considering the low temperature of the plume under the tested conditions, it appears that the ionisation in the plasma plume is dominated by that of the metal atoms present, which have a much smaller ionisation energy. This implies that the ionisation of the shielding gas has a negligible influence on the breakdown behaviour.
Fig. 3.13 Influence of shielding gas on the breakdown voltage (electrode negative).

Fig. 3.14 Influence of shielding gas on the breakdown voltage (electrode positive).

Experiments were also performed in open air. It was found that under electrode negative conditions at 3 mm electrode-workpiece distance no
breakdown occurs up to a voltage of 250 V. Under electrode positive conditions, the current in the oscillogram turned out to be discontinuous and breakdown was found to occur irregularly. The observed behaviour can be ascribed to two phenomena. Firstly, oxygen and nitrogen molecules are electron negative and, hence, capture electrons, which reduces the number of electrons in the plume. Secondly, the presence of oxygen leads to oxidation of the metal particles in the plume, especially when spatter occurs. The metal oxide particles will deposit on the electrode surface and thus form an electrically isolating barrier. On the basis of the foregoing it can be concluded that the presence of air in the shielding gas hampers breakdown.

3.4 DISCUSSION

The obtained results presented in the previous section can be qualitatively explained in more detail by considering the development of the current between electrode and workpiece.

Consider the situation of a workpiece and an electrode, which are separated by a distance d. When a laser beam is focused on the workpiece surface, laser energy is transferred to the metal and, consequently, the metal temperature rises rapidly. If the amount of transferred energy is sufficiently large, the metal will locally melt and vaporise and a plasma plume is formed. This plasma plume consists mainly of metal vapour, which due to its high temperature is partially ionised and, hence, electrons and positive ions are present in the space between workpiece and electrode. In addition to the formation of a plasma plume, free electrons are produced in a thin region above the metal surface by thermionic emission.

When a voltage V is applied between the electrode and the workpiece, the electrons drift towards the anode, whereas the positive ions drift towards the cathode. This results in an electric current, which is equal to
\[ I = (n_e v_e + n_i v_i) e \] (3.1)

where \( n_e \) is the electron density, \( n_i \) the density of positive ions, \( v_e \) the average drift velocity of the electrons, \( v_i \) the average drift velocity of the positive ions and \( e \) the electron charge.

As long as the electric field strength is sufficiently small, the current remains constant in time (steady state current).

It is expected that under EP conditions this steady state current is larger than under EN conditions, since in the first case the electrons emitted by the cathode (being the heated workpiece) also contribute to the current. It is also expected that both under EP and under EN conditions the current increases with increasing field strength. These expectations are consistent with the experimental results obtained (see Figs. 3.3 and 3.5).

As mentioned earlier, the foregoing description of the steady state situation is only valid as long as the electric field strength is sufficiently small. With increasing electric field strength the situation becomes more complex due to the increasing importance of collisional ionisation taking place in the space between electrode and workpiece. Energy transfers from electrons to neutral atoms during collisions and this gives rise to an exponential production of electrons and positive ions (avalanche ionisation). The number of electrons and positive ions produced in an avalanche is \( n_0 e^{\alpha v} \), where \( n_0 \) is the number of electrons originally present and \( \alpha \) the ionisation rate (the number of ionisation per electron per volt) [3.7].

The positive ions (originally present in the plasma plume, together with those produced by avalanche reactions) move towards the cathode and, on arrival, bombard the cathode surface. In this way the positive ions transfer energy to the cathode, which stimulates thermionic emission. If the number of electrons \( \mu \) generated from the cathode surface by one original electron satisfies:
\[ \mu = \gamma(e^{av} - 1) > 1 \]  \hspace{1cm} (3.2)

where \( \gamma \) is called the secondary electron emission coefficient of the cathode, the ionisation between the electrodes will grow to a maximum, which is reflected by the maximum current allowed by the external circuit. Consequently, the gap between the electrodes becomes highly conductive. In fact, when a welding power source is used, an arc is formed (ignition).

It is believed that stimulation of thermionic emission as described in the foregoing is the main cause of the observed reduction of the breakdown voltage in the presence of a laser-induced plasma plume. The fact that under EP conditions the breakdown voltage is somewhat smaller than under EN conditions can be understood by realizing that under EP conditions the cathode (workpiece) is heated by the laser beam, resulting in extra stimulation of thermionic emission.

In addition to promoting thermionic emission, positive ions can also enhance \( \gamma \) by the probability of field emission [3.8]. This is caused by the fact that a positive ion sheath will be formed in front of the cathode, due to the slow neutralisation of the positive ions. This sheath continues to build up, resulting in an increase of the electric field strength in front of the cathode. When the electric field strength reaches a critical level, field emission will start to occur from the lowest emission potential sites on the cathode surface. Field emission is likely to play a role under EN conditions where the cathode is relatively cold. It is an irregular process and in its initial stage it is characterised by current peaks of short duration. This behaviour is clearly illustrated by the results presented in Fig. 3.4.
3.5 CONCLUSIONS

This chapter deals with the possibilities of using the laser-induced plasma plume as a tool to facilitate the ignition of the welding arc. The obtained results lead to the following conclusions.

1) The breakdown voltage required for ignition of the welding arc is significantly reduced by the presence of a laser-induced plasma plume.

2) Under electrode positive conditions (the electrode is connected to the positive pole of the DC power source), the observed reduction of the breakdown voltage is caused by stimulated thermionic emission.

3) Under electrode negative conditions (the electrode is connected to the negative pole of the DC power source), enhanced field emission also plays a role.

4) The breakdown voltage increases with increasing laser energy density under the tested conditions. This is due to the higher pressure generated inside the plume by the severe evaporation and the appearance of strong fluctuations in the current and spatter at high laser energy.

5) The breakdown voltage depends on the type of the shielding gas used. Argon leads to a lower breakdown potential than helium. Air hampers the current/ionisation development between the electrodes by electron capture and oxidation of the metal.
REFERENCES


INFLUENCE OF LASER RADIATION ON WELDING ARC STABILITY

The laser-induced arc stabilising effect is one of the major benefits of the laser-arc hybrid welding system. In this chapter, the results are presented of experiments, which were conducted with the aim to test the various situations where the GTA welding process cannot produce a stable weld bead. A laser-induced stabilising mechanism is proposed based on the minimum energy principle. Additionally, the absorption of laser energy by the arc plasma and the changes of plasma composition caused by the laser radiation are measured using a laser energy meter and an emission spectroscope.
CHAPTER 4 INFLUENCE OF LASER RADIATION ON ARC STABILITY

4.1 INTRODUCTION

In the study of the hybrid laser-arc welding process, the beneficial influence of the laser radiation on arc stability is often mentioned as an important phenomenon [4.1-4.4]. The mechanisms proposed for the observed laser-induced stabilising effect are either associated with a greater electron density in the laser-induced plasma plume [4.1] or with the fact that the laser provides a favourable anode spot for the arc [4.2-4.4]. However, both approaches are rather speculative and detailed information at this point is at present not available.

Arc stability is a complex phenomenon. In this study, an unstable arc means that the arc deviates irregularly from the shortest path between the workpiece and the electrode tip, which results in an irregular weld bead when the welding torch travels linearly with respect to the workpiece.

An arc is composed of three parts: the cathode fall region, the arc column and the anode fall region. Therefore, an unstable arc can be due to the occurrence of instability of either one of these regions or their combination.

Adding a laser beam to the arc makes the situation more complicated, the stability of the combination being also dependent on the different laser characteristics and workpiece properties.

In this chapter, the results are presented of tests, which were carried out to explore the various instabilities of the arc and to examine the influence of Nd/YAG laser radiation on these instabilities. The laser used has a wavelength of 1.06 μm and works at a power level of maximum 500 W. As this laser power is relatively low, the combined laser-arc welding process is called Laser-assisted Arc Welding (LAW). On the basis of the results of these tests an explanation is proposed of the laser-induced arc stabilisation. Laser energy absorption and spectroscopic measurements were performed in order to validate the explanation.
4.2 EXPERIMENTAL

The experimental set-up used consists of standard GTA welding equipment and a HAAS 506D laser (Nd/YAG laser, continuous wave). Detailed information about the GTA welding equipment and the laser beam is given in Table 4.1. The workpiece materials used were mild steel Fe 360 and the aluminium alloy AA 6061 in the form of plates having dimensions 250×100×4 mm. Before the experiments the surface of the workpiece was cleaned with acetone.

Table 4.1 Technical data of the set-up of laser-assisted arc welding.

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>mild steel Fe 360 and AA 6061 (250×50×4 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td>tungsten (2% Th), Ø 2.4 mm, 60 degree tip angle</td>
</tr>
<tr>
<td>Polarity</td>
<td>electrode negative (EN)</td>
</tr>
<tr>
<td>Electrode tip position</td>
<td>4 mm above workpiece and 2.5 mm from laser beam centre</td>
</tr>
<tr>
<td>Nd/YAG laser</td>
<td>500 W continuous wave</td>
</tr>
<tr>
<td></td>
<td>wave length 1.06 μm</td>
</tr>
<tr>
<td></td>
<td>focus spot diameter 0.3 mm (7.1×10^5 W/cm²)</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>argon (12 l/min)</td>
</tr>
</tbody>
</table>

To determine the energy transfer from the laser beam to the arc plasma measurements were performed using a laser energy meter of the type Ophir 5000 W-LP.

For the spectroscopic measurements, a lens with a 25 mm focal length and an optical fibre with a 0.6 mm diameter were used to transmit the arc plasma light into the monochrometer (Perkin Elmer Plasma II). The specification of the
monochrometer is given in Table 2.3 of Chapter 2. A schematic drawing of the set-up is shown in Fig. 4.1.

Fig. 4.1 Experimental set-up.

4.3 RESULTS AND DISCUSSION

4.3.1 INFLUENCE OF LASER RADIATION ON ARC STABILITY

The influence of Nd/YAG laser radiation on arc stability was examined by carrying out tests under different experimental conditions using both mild steel Fe 360 and the aluminium alloy AA 6061 as workpiece.

For mild steel Fe 360 tests were conducted using the following two welding procedures: i) low welding current bead-on-plate welding, and ii) welding under asymmetric magnetic field conditions.

i) When the welding current is low, the arc anode may change from diffusion mode to restricted mode [4.5]. In the case of the restricted mode the
arc jumps and weaves while the welding torch travels along its prescribed path. Experiments show that under these conditions melting of the workpiece is irregular and an irregular weld bead is formed. However, this irregularity disappears after the laser beam joins in: the arc root is fixed to the laser spot, which leads to a uniform weld bead as shown in Fig. 4.2.

![Image](image_url)

**Fig. 4.2** Top view of bead-on-plate weld in mild steel Fe 360 (arc current 50 A, travel speed 4 mm/s).

ii) To create an asymmetric external magnetic field, a block of ferritic steel was positioned beside the arc passing route. As a consequence of this, the magnetic field strength on the steel block side of the welding route is higher than on the other side. It was found that in the case of GTA welding when the arc passes the steel block, the arc does not remain extended vertically beneath the electrode, but tends to bend towards the steel block, thus producing an irregular weld bead as shown in Fig. 4.3a. However, in the case of LAW, the irregular movement of the arc disappears and a straight weld bead is produced as shown in Fig. 4.3b.
Fig. 4.3 Top view of bead-on-plate welds in mild steel Fe 360 under asymmetric external magnetic field conditions: a) GTAW, b) LAW (arc current 60 A, travel speed 4 mm/s).

Tests on the aluminium alloy AA 6061 were conducted using both argon and helium as the shielding gas. The results presented in Fig. 4.4 show that in the case of argon as the shielding gas, the arc root changes from completely unstable in the case of GTA welding to stable in the case of LAW. Arc stability can also be monitored in terms of variations in the arc voltage as demonstrated
in the lower part of Fig. 4.4. It can be seen that in the case of LAW the variation in arc voltage is reduced, whereas the average value of the voltage is smaller than in the case of GTAW.

Fig. 4.4  Top view of bead-on-plate weld in AA 6061 produced with argon as the shielding gas and corresponding voltage-time plot (arc current 80A, travel speed 4 mm/s).

The results presented in Fig. 4.5 show that in the case of helium as the shielding gas, even at very short arc length, the arc stability can still be improved by laser radiation.
It should be remembered that the 500 W Nd/YAG laser radiation alone cannot melt the aluminium alloy due to the strong surface reflection of the laser beam as mentioned in Chapter 2.

Fig. 4.5 Top view of bead-on-plate welds in AA 6061 produced by helium as the shielding gas together with corresponding voltage-time plot (arc current 85 A, travel speed 8 mm/s and arc length 2 mm).
4.3.2 STABILISATION MECHANISM

The experimental results presented above prove that 500 W Nd/YAG laser radiation can stabilise the electric arc under various conditions. However, in order to explain the underlying mechanism(s) more detailed analysis of the stabilising effect is required.

It is well known that an electric arc selects the route between electrode and workpiece, which consumes the least electrical energy. The laser radiation stabilising effect therefore can be considered from a least energy point of view.

The energy conservation of the electrons in a two-temperature plasma can be expressed by the following equation [4.6-4.7]:

\[ \nabla \cdot (k_e \nabla T_e) + \left( 2.5 + \frac{\frac{e \phi}{k_B \sigma}}{e} \right) k_B \cdot \nabla T_e + JE \]

\[ = \left( \frac{5}{2} k_B T_e + \varepsilon_i \right) \dot{n}_e + \frac{3 m_e}{m_i} k_B (T_e - T_i) n_e \bar{v}_e + \dot{R} \]

(4.1)

with \( k_e \) the electron thermal conductivity, \( \phi \) the thermal diffusion coefficient, \( \sigma \) the electrical conductivity, \( m_e \) the mass of the electron, \( m_i \) the mass of the ion, \( T_e \) the electron temperature, \( T_i \) the heavy particle temperature, \( k_B \) the Boltzmann constant, \( J \) the current density, \( E \) the electrical field strength, \( \dot{n}_e \) the net electron production rate, \( n_e \) the electron density, \( e \) the electron charge, \( \varepsilon_i \) the ionisation potential, \( \bar{v}_e \) the average collision frequency between electrons and ions and \( \dot{R} \) the radiation loss.

In the equation the left hand side contains the energy input to the electrons: a heat conduction term, an electron thermal energy term and the energy input from Joule heating respectively. The right hand side of the equation contains the energy consumption part: energy necessary for generation of electrons, energy loss in collisions with heavy particles and radiation loss, respectively.
In the case of LAW, modifications must be made in the above equation to be able to properly describe the arc plasma after the laser beam joins in. More specifically, in the case of LAW the energy input part should include: i) direct heating of the plasma by the laser beam, whereas the energy consumption part should take into account that: ii) the metal atoms pushed into the plasma by evaporation have a low ionisation energy and a high initial temperature, iii) the radiation loss increases due to the higher emission coefficient of the iron-argon mixture plasma [4.8].

Thus after the modifications described in the foregoing the energy conservation equation of the electrons in the LAW plasma becomes:

\[ \nabla \cdot (k_e \nabla T_e) + (2.5 + \frac{e\phi_{eb}}{k_b \sigma_e} J) \cdot k_b \cdot \nabla T_e + JE + H_1 = \]

\[ \left(\frac{5}{2}k_b T_e + \epsilon_e'\right) \dot{n}_e' + \frac{3m_e}{m_i} k_b (T_e - T_b) n_i \bar{v}_{ei} + \dot{R}' \]

with $H_1$ the laser energy absorbed by the arc plasma, $\epsilon_e'$ the modified ionisation potential, $\dot{n}_e'$ the modified electron production rate and $\dot{R}'$ the modified radiation loss.

The results of the experiments on the laser-induced stability presented in section 4.3.1 prove that under the tested conditions the arc is stabilised in the laser spot, which means that the term $JE$ of the arc in equation 4.2 has its lowest value in the laser spot due to the energy changes caused by $H_1$, $\epsilon_e'\dot{n}_e'$ and $\dot{R}'$ in the modification.

The radiation loss term $\dot{R}'$ can be calculated theoretically when the plasma composition change and temperature are known [4.8]. In the following sections, the modification terms i and ii are considered in more detail. Specifically, experiments were conducted to examine the direct heating of the
plasma by the laser beam and the composition change in the plasma due to the laser induced evaporation.

4.3.3 DIRECT HEATING OF PLASMA BY LASER BEAM

To measure the direct heating of the plasma by the laser beam, experiments were conducted making use of a laser energy meter. In these experiments the horizontally placed laser beam (500 W continuous wave) is focused by an optical lens into the central part of the arc, which burns between a tungsten cathode and a water cooled tungsten anode, after which the beam disperses again and finally enters a laser energy meter. The laser energy meter reads out the input laser power as function of time. The set-up used is shown in Fig. 4.6.

![Diagram of a laser setup](image)

**Fig. 4.6** Experimental set-up for measuring of the direct heating of a plasma by a laser beam.

Preliminary tests show that in the case of 500 W laser energy the laser energy meter needs about 50 ~ 60 seconds to reach its equilibrium. For this
reason all measurements were conducted to last a fixed time of 150 seconds, and only the readings from the last 90 seconds are taken into consideration.

Experiments were carried out with the laser and the arc turned on separately and with the laser and the arc working simultaneously.

It was found during the experiments that the reading of the laser energy meter had a strong dependence on the cooling flow unit. Therefore, a pump with a constant flow rate was used for the cooling and the temperature of the cooling water was controlled to vary within one degree Celsius throughout the measurements.

The experiments were conducted with a constant arc length of 4 mm and the laser beam was focused at exactly the centre of the arc. Use was made of a laser lens having a 100 mm focal length and producing a 0.3 mm diameter focal spot, resulting in a laser power density of $7.1 \times 10^5$ W/cm$^2$, which is the same as that used in previous experiments (see section 4.3.1).

The results of the measurements carried out at an arc current of 50 A are shown in Fig. 4.7. Although the curves in the figure show strong fluctuations, it can be seen that the sum of the laser power and the arc power when operating separately (arc+laser) is larger than the power of the hybrid system (arc/laser). More specially, it appears that on average, about 1.26 W or 0.28% of the 500 W laser energy is lost when the beam passes through the arc plasma.
Fig. 4.7  Measured power as function of time for 500 W laser, sum of 500 W laser and 50 A arc (arc+laser) and 500 W laser/50 A arc hybrid system (arc/laser).

Increasing the arc current to 100 A results in the power versus time plots, which are shown in Fig. 4.8. This time the difference between the two situations is considerably larger. As shown in the figure, on average 3.2 W or 0.7% of the 500 W laser energy is lost when the beam passes through the arc.
Fig. 4.8 Measured power as function of time for 500 W laser, sum of 500 W laser and 100 A arc (arc+laser) and 500 W laser/100 A arc hybrid system (arc/laser).

The attenuation of a laser beam travelling through a plasma can be expressed as:

\[ I = I_0 \exp(-\mu L) \]  \hspace{1cm} (4.3)

with \( I \) and \( I_0 \) the attenuated and the initial laser beam intensity, \( L \) the plasma length and \( \mu \) the absorption coefficient. Calculation of \( \mu \) using the experimental results with \( L = 0.5 \) cm for an arc at 100 A arc current yields a value of \( 1.03 \times 10^2 \) /cm. This value agrees with the theoretical calculation obtained by Hughes [4.9].

It is well known that in the case of a plasma having a high temperature and a high charged particle density, such as a welding arc, the electron-ion inverse bremsstrahlung (IB) process becomes the dominant mechanism for the laser energy absorption by the plasma. The IB absorption coefficient \( \mu \) is given by equation [4.10]:

\[ \mu = n_n Z^2 e^4 \ln(\frac{2.25 k_n T_e}{h \nu}) \lambda^2 \]
\[ / [24 \pi^2 e^4 m_ee^4 m_e^2 \lambda(2 \pi m_e k_B T_e)^{1/2} ] \]  \hspace{1cm} (4.4)

where \( Z \) is the charge number, \( e \) the electronic charge, \( c \) the velocity of light in vacuum, \( \epsilon \) the permittivity of free space, \( \nu \) and \( \lambda \) the frequency and wavelength of the laser beam and \( n \) the refractive index of the plasma.

As shown in the equation, the absorption coefficient is proportional to the square of the laser beam wavelength. This indicates that a welding arc does not effectively absorb short wavelength laser radiation, which is in agreement with the obtained experimental results.

Nevertheless, one should bear in mind that when metal vapour enters the arc as in the case of LAW, the absorption coefficient can be more than several
times higher than that in the case of a pure argon plasma as calculated by Szymanski and Kurzyna [4.11], which makes the 500 W laser direct heating of the arc no longer negligible in the energy equation 4.2.

4.3.4 SPECTROSCOPIC MEASUREMENTS OF THE CHANGE IN PARTICLE COMPOSITION

It has been shown in the foregoing that the strong metal evaporation of the workpiece induced by the laser radiation can greatly change the nature of the arc. Having much lower excitation and ionisation energy levels, the metal atoms will be more easily excited and ionised in the metal-argon mixture arc, which reduces the energy necessary for ionisation.

To examine the change in particle composition of the plasma caused by the introduction of the laser, spectroscopic measurements were conducted. The specifications of the spectrometer used are listed in Table 2.3. Welding was carried out with steel Fe360 as workpiece material under the conditions of 4 mm/s travel speed, 100 A arc current and 4 mm arc length. Two regions in the arc were examined: 1 mm beneath the electrode tip and 1 mm above the workpiece surface. The situation is illustrated in Fig. 4.9. The emission lines of argon and iron to be measured were selected on their measurability, which means that they should have a strong intensity and no interference with neighbour lines, whereas at the same time reliable data for further calculations should be available. Thus, five iron lines and five argon lines were considered, their wavelengths being listed in Table 4.2. Measurements of the intensity of these lines were performed under the standard arc conditions with and without laser radiation. The results are plotted in Figs. 4.10 and 4.11 and indicate that in the case of GTA welding, minor amounts of Fe ions are present in the arc plasma, whereas in the case of LAW, the intensity of the Fe II line and hence
the amount of Fe ions is much higher throughout the arc. At the same time the intensity of the argon lines is significantly smaller than in the case of GTAW.

![Diagram]

**Fig. 4.9** Illustration of the spectroscopic measuring positions.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>g_k</th>
<th>ArII line</th>
<th>A_k</th>
<th>E_k (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>434.806</td>
<td>8</td>
<td></td>
<td>1.24×10⁸</td>
<td>157234</td>
</tr>
<tr>
<td>458.990</td>
<td>6</td>
<td></td>
<td>8.20×10⁷</td>
<td>170401</td>
</tr>
<tr>
<td>472.686</td>
<td>4</td>
<td></td>
<td>5.00×10⁷</td>
<td>159393</td>
</tr>
<tr>
<td>476.486</td>
<td>4</td>
<td></td>
<td>5.75×10⁷</td>
<td>160239</td>
</tr>
<tr>
<td>480.602</td>
<td>6</td>
<td></td>
<td>7.90×10⁷</td>
<td>155043</td>
</tr>
</tbody>
</table>
### FeII line

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>$g_k$</th>
<th>$A_k$</th>
<th>$E_k$ (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>259.154</td>
<td>6</td>
<td>$5.20 \times 10^7$</td>
<td>46967</td>
</tr>
<tr>
<td>259.278</td>
<td>16</td>
<td>$2.25 \times 10^8$</td>
<td>71433</td>
</tr>
<tr>
<td>266.466</td>
<td>10</td>
<td>$1.50 \times 10^8$</td>
<td>64832</td>
</tr>
<tr>
<td>275.329</td>
<td>12</td>
<td>$1.71 \times 10^8$</td>
<td>62662</td>
</tr>
<tr>
<td>451.534</td>
<td>6</td>
<td>$1.80 \times 10^5$</td>
<td>45048</td>
</tr>
</tbody>
</table>

---

![Graph GTAW](image)

$y = -1.2x + 4.3$

($T_e = 9667$ K)

![Graph LAW](image)

$y = -1.2x + 4.0$

($T_e = 9667$ K)

Fig. 4.10a Intensities of the ArII lines in anode region (point 1 of Fig. 4.9) under GTAW and LAW conditions.
Fig. 4.10b  Intensities of the FeII lines in anode region (point 1 of Fig. 4.9) under GTAW and LAW conditions.
Fig. 4.11a Intensities of ArII lines at cathode region (point 2 of Fig. 4.9) under GTAW and LAW conditions.
Fig. 4.11b Intensities of FeII lines at cathode region (point 2 of Fig. 4.9) under GTAW and LAW conditions.

According to the Boltzmann distribution law in a LTE plasma [4.12]:

\[
\frac{n_k}{n} = \frac{g_k}{Q} \exp\left(-\frac{E_k}{k_B T_e}\right) \tag{4.5}
\]

with \(n_k\) the density of the ionised atoms in the energy state \(k\), \(g_k\) their statistical weight, \(E_k\) their upper energy level, \(T_e\) the temperature, \(k_B\) the...
Boltzmann constant, Q the partition function and n the density of the ionised atoms regardless of their energy state. Furthermore, the emission intensity can be expressed by the equations [4.12]:

\[ I_k = \int e_k \, dx \]  

(4.6)

and

\[ e_k = \frac{hv}{4\pi} A_k n_k \]  

(4.7)

with \( I_k \) the emission intensity, \( e_k \) the emission coefficient, \( x \) the thickness of the plasma source, \( A_k \) the transition probability, \( h \) the Planck constant and \( v \) the frequency of the emission line.

The particle density ratio between iron ions and argon ions can now be estimated from the measured emission intensities using equations 4.5 to 4.7. The results of this estimation are given in Table 4.3 and indicate that a large amount of metal vapour enters the arc by the action of the laser. In fact, the metal vapour induced by the laser radiation dominates the composition of the arc in the space close to the workpiece (anode region).

<table>
<thead>
<tr>
<th>Table 4.3 Ratio between ArII and FeII calculated from experimental data using the Boltzmann law.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode region</td>
</tr>
<tr>
<td>FeII / ArII ≡ 4 \times 10^{-2}</td>
</tr>
<tr>
<td>Anode region</td>
</tr>
</tbody>
</table>

This means that in the case of LAW, a large amount of metal atoms produced by the evaporation is involved in the arc plasma ionisation. They replace the ions of the shielding gas due to their relatively low ionisation potential and hence reduce the total arc plasma ionisation energy. When the
laser spot and the evaporation are stable, the metal vapour flows upwards in a stationary way; thus it builds a stable plasma channel for arc root and column that overcomes disturbing external forces. The arc thus is stabilised as shown in the stabilising experiments described in section 4.3.1.

Extra information about the arc plasma can be obtained by considering the average electron temperature. This temperature can be calculated by means of a Boltzmann plot [4.12] using the results of the spectroscopic measurements:

\[
\ln\left(\frac{I}{A_{\text{gy}}}\right)_k = C - \frac{E_k}{k_B T_e}
\]

where \(C\) is a constant.

According to equation 4.8 the slopes of the trend lines through the data points of Figs 4.10 and 4.11 are an indication of the temperature. It turns out that the average electron temperature is lower under LAW conditions than under GTAW conditions. The results correspond with the fact that the iron ionisation energy is much lower than that of argon, which enables the plasma to reach the electron density required to carry the current at a lower temperature. In the figures the linear relationship between the intensities of the emission lines and energy stage validates the existence of LTE conditions in the measurement regions.

4.4 CONCLUSIONS

This chapter deals with the influence of laser radiation on the arc stability. The obtained results lead to the following conclusions.

1) The welding arc can be effectively stabilised by a Nd/YAG laser beam of moderate power (500 W).

2) A stabilising mechanism is proposed, which is based on the minimum energy principle: the arc current flows along a path around the laser beam because of the minimum electrical resistance.
3) The absorption of a Nd/YAG laser beam by a welding arc is measured by horizontally passing the beam through an argon arc plasma and determining the final laser energy by means of a laser energy meter. The results show that about 0.28% and 0.7% of the 500 W laser beam energy is absorbed when the arc currents are 50 A and 100 A respectively.

4) Spectroscopic measurements show that the metal atoms generated by the evaporation replace part of the ions from the shielding gas due to their lower ionisation potential. The metal-argon mixture plasma forms a stable arc root and arc column channel.
REFERENCES


ARC MANIPULATION BY MEANS OF A LASER BEAM

Experiments show that arc manipulation and control by a laser beam gives the laser-assisted arc welding system a number of advantages over the standard GTA welding system, such as improved possibilities for welding of thick-thin plate combinations, asymmetric edges and dissimilar materials. In this chapter, arc manipulation possibilities are examined with emphasis on two aspects: geometrical limitation of arc root movement and arc column constriction (resulting in change of the arc current density) due to the laser radiation.
5.1 INTRODUCTION

In the previous chapter attention was given to the interaction between a laser beam and the welding arc. It was shown that (under specific conditions) the laser attracts the arc, which suggests that it is possible to manipulate the position and the shape of the welding arc by a laser beam. Preliminary research carried out in co-operation with Philips CFT also confirmed the manipulation possibilities of a micro-arc under stationary conditions by a pulsed laser [5.1].

The manipulation of a welding arc by a laser beam may result in many practical applications such as spot-welding of tiny electronic devices in the electronic industry and arc root position control under high-speed welding conditions [5.2]. Specific welding problems can also occur in the case of GTA welding of thick-thin material combinations, asymmetric edges and dissimilar materials, as shown in Fig. 5.1. In these cases desirable weld beads might not be produced due to asymmetric heat transfer caused by deviation of the welding arc. Under such circumstances, it would be ideal if it were possible to manipulate and control the arc and to force it to the right position by a laser beam.

In this chapter the results are presented of the experiments, which were conducted to examine the possibilities of arc manipulation by a laser beam. Attention was also given to various influencing factors and it was shown that the laser beam not only can control the arc column and root position, but also can constrict the volume of the arc, thus redistributing the electric current within the arc. Split-anode measurements were conducted to analyse the arc current distribution induced by the laser radiation. Possible applications of arc manipulation are described at the end of the chapter.
5.2 EXPERIMENTAL PROCEDURE

The experimental set-up used consists of standard GTAW equipment in combination with a HAAS 506D laser (Nd/YAG continuous wave, max. 500 W) as shown in Fig. 5.2. Detailed information about the set-up is listed in Table 4.1.

The workpiece used in the experiments is mild steel Fe 360 in the form of plates having dimensions of 250×50×2 mm for position measurements and 100×50×10 mm for split-anode measurements. The surface of the workpiece is cleaned before welding with acetone. Argon with a constant flow of 12 l/min is used as the shielding gas.

The working principle of the split-anode measurements is schematically shown in Fig. 5.3. A ceramic sheet with a thickness of 0.15 mm is placed between the two steel pieces to isolate the two parts of the anode, making it possible to measure the current through each part separately. The welding current as function of time is controlled and recorded by a personal computer using the LabVIEW programme for further calculations.
**CHAPTER 5  ARC MANIPULATION BY MEANS OF A LASER BEAM**

![Diagram](image)

**Fig. 5.2** Schematic drawing of the experimental set-up.

![Diagram](image)

**Fig. 5.3** Schematic drawing of the set-up for split-anode measurements.
5.3 RESULTS AND DISCUSSION

5.3.1 MANIPULATION OF ARC ROOT POSITION BY A LASER BEAM

Using the set-up described in the previous section, experiments were conducted under various conditions. The experimental results show that under either stationary or travelling conditions when a laser beam irradiates the workpiece close to the root of an electric arc, depending on the circumstances, the electric arc can be completely coupled with the laser beam spot. Under these conditions the weld pool formed will be centred at the laser beam spot. The results thus indicate that the laser beam has an arc manipulation capability.

The effectiveness of the laser manipulation depends on the properties of the arc and the properties of the laser beam. The main influencing parameters of the arc are: 1) arc current, 2) arc length and 3) travel speed. It was found that in general the lower the arc current, the higher the arc length and the lower the travel speed, the easier the arc can be manipulated by a laser beam. On the laser beam side, the influencing properties are 1) the laser power level and 2) the beam focusing position with respect to the electrode projection point. The experimental results indicate that the higher the laser power the better its manipulation ability. Furthermore, it appears that there is a geometrical limitation to the beam focusing position for arc manipulation. The limitation range for complete coupling of an arc with a 500 W laser at arc length 5 mm and travel speed 4 mm/s is given in Table 5.1.
Table 5.1 Arc manipulation range of 500 W laser (arc length 5 mm, travel speed 4 mm/s).

<table>
<thead>
<tr>
<th>Arc current</th>
<th>Manipulation range</th>
</tr>
</thead>
<tbody>
<tr>
<td>30A</td>
<td>2 mm forward/backward, 3 mm sideward</td>
</tr>
<tr>
<td>50 A</td>
<td>2 mm forward/backward, 2 mm sideward</td>
</tr>
<tr>
<td>75 A</td>
<td>2 mm forward/backward, 1 mm sideward</td>
</tr>
<tr>
<td>100 A</td>
<td>2 mm forward/backward, 1 mm sideward</td>
</tr>
</tbody>
</table>

The physical background of arc manipulation by a laser beam can be understood in terms of the minimum energy principle discussed in the previous chapter: the electric energy consumption of the arc/laser combination is less than that when the arc maintains its original position. Therefore, the theoretical limitation of arc manipulation is determined by the position for which the two energies become equal. The energy change caused by the laser radiation according to equation 4.2 in the case of arc manipulation can be expressed as:

\[-H_i + \varepsilon_i \dot{\hat{n}}_e + \dot{R} \leq \varepsilon_i \dot{\hat{n}}_e + \dot{R}\]  

(5.1)

The terms on the left side describe the plasma in the arc/laser combination: \(H_i\) is the laser energy absorbed by the arc, \(\varepsilon_i\) the ionisation potential of the argon-metal mixture, \(\hat{n}_e\) the electron production rate and \(\dot{R}\) the radiation loss of the laser-manipulated arc; the terms on the right side describe the original arc: \(\dot{\hat{n}}_e\) is the net electron production rate, \(\varepsilon_i\) the ionisation potential of argon and \(\dot{R}\) the radiation loss of the original arc. The foregoing implies that the manipulation possibility depends on the arc absorption of the laser beam energy, the metal atoms in the plasma and the change of the total amount of the net electron production.
5.3.2 CURRENT REDISTRIBUTION WITHIN THE ARC

The results of the experiments presented above indicate that there is a maximum range for arc manipulation by a laser beam. When the arc current increases, this maximum becomes increasingly smaller as shown in Table 5.1. Furthermore, the experiments show that even when the maximum range of arc manipulation becomes limited at high current, the arc column shape is still influenced by the laser radiation. This is demonstrated in the photographic images of a 100 A arc without and with laser beam radiation as presented Fig. 5.4, which clearly show that the arc column with the laser beam becomes narrower than the arc column without the laser beam. If the shape of the arc column changes, the arc current distribution changes accordingly, which could be regarded as another aspect of arc control and manipulation.

To further examine the influence of laser radiation on the arc current distribution, split-anode current distribution measurements were conducted. The principle of this type of measurement is to track the arc current change during the period the arc travels from one part of the workpiece to the other as shown in Fig. 5.3.

With the help of the Abel inversion algorithm the current distribution in the arc was calculated using the obtained plot of current as function of time [5.3]. In this calculation the arc root was assumed to have a circular shape. The results of the measurements show that in the case of a low arc current, the arc changes from unstable to stable when the laser is added to the arc. The results for a 30 A arc with laser radiation are shown in Fig. 5.5. Without the laser beam, the arc is unstable and the current density distribution is fluctuating and cannot be measured. The results for a higher current arc (80 A) without and with laser are shown in Figs. 5.6 and 5.7. It can be seen that under these conditions the arc current density increases when a laser beam is added, which agrees well with the arc column constriction shown in Fig. 5.4.
Fig. 5.4 Photographic images of 100 A arc in the case of GTAW (above) and in the case of LAW (below) at a travel speed of 4 mm/s.
Fig. 5.5  Arc current versus time (above) and calculated arc current density distribution (below) for a 30 A arc in combination with a 400 W laser beam (arc length 4 mm, travel speed 8 mm/s).

Fig. 5.6  Arc current versus time (above) and calculated arc current density distribution (below) for an 80A arc without laser (arc length 4 mm, travel speed 8 mm/s).
Fig. 5.7 Arc current versus time (above) and calculated arc current density distribution (below) for an 80 A arc in combination with a 500 W laser beam (arc length 4 mm, travel speed 8 mm/s).

The observed arc constriction phenomena is mainly due to the injection of a large amount of metal vapour in the arc plasma. Comparing the atomic ionisation of a pure argon plasma with that of an iron-argon plasma, the effect of iron atoms in the arc plasma is especially apparent in the low temperature region as shown in Fig. 5.8 [5.4]. This low temperature region corresponds to the temperature region of the welding arc, where due to the presence of iron atoms the electron density and hence the electric conductivity increase strongly as illustrated by the following equation [5.5]:

\[
\sigma_e = \frac{n_e e^2}{\sqrt{2\pi T m_e n_a \sigma_{en}}}
\]  \hspace{1cm} (5.2)

with \(\sigma_e\) the electrical conductivity, \(n_a\) the neutral particle density, \(\sigma_{en}\) the electron-neutral particle collision cross-section, \(m_e\) the mass of the electron and \(T\) the plasma temperature.
The increased plasma electrical conductivity consequently of the plasma results in the constricted arc column.

![Graph showing particle density as a function of temperature for an iron-argon mixture plasma](image)

Fig. 5.8  Particle density as a function of temperature of an iron-argon mixture plasma [5.4].

5.3.3 APPLICATIONS

The arc root position control together with the current distribution manipulation gives the laser-assisted arc welding (LAW) process a number of advantages over the standard GTAW process. Experiments were conducted to illustrate these advantages for three specific welding situations.

i) Welding of think-thin material combination

Single-pass butt welding of a 4 mm thick plate and a 2 mm thick plate was carried out using the GTAW process and the LAW process. The results are
shown in Fig. 5.9 in the form of transverse weld cross-sections. It can be seen that in the case of GTAW, a large weld is formed with its centre at the thin plate side, whereas the connecting part of the thick plate side is insufficiently molten. The formation of this asymmetric weld is caused by electro-magnetic deviation of the arc and by the asymmetric heat sink. Using the laser manipulation capability of the arc by focusing a laser beam on the thick plate side, a uniform weld bead over both plates is produced.

![Image of weld cross-sections]

Fig. 5.9 Thick-thin butt weld in Fe 360 in the case of GTAW (above) and LAW (below).
GTAW: current 230 A, travel speed 8 mm/s; LAW: current 150 A, travel speed 8 mm/s and laser power 500 W.
ii) Edge welding

As shown in Fig. 5.10 the weld bead formed in the case of GTA edge welding deviates toward the horizontal side leaving an unwelded region at the inner side of the joint. This is again due to the asymmetric heat sink in combination with the electro-magnetic forces. Using the laser beam to direct the arc root toward the vertical plate (by focusing the laser beam on the surface of the vertical plate) a good weld bead is easily produced.

![Image](image-url)

Fig. 5.10 Edge joint in steel Fe 360 in the case of GTAW (above) and LAW (below).
GTAW: current 160 A, travel speed 8 mm/s; LAW: current 110 A, travel speed 8 mm/s and laser power 500 W.
iii) Welding of dissimilar materials
Mild steel Fe 360 and stainless steel AISI 304 plates were butt-welded using the GTAW and LAW processes respectively. The results are shown in Fig. 5.11. In the case of GTAW, the low heat conductivity of the stainless steel compared with that of the mild steel results in preferred melting of the stainless steel part and insufficient melting of the mild steel part. In the case of LAW, a better mixed weld bead is produced due to the arc manipulation capability of the laser.

Fig. 5.11 Welding of stainless steel AISI 304 to mild steel Fe 360 in the case of GTAW (above) and LAW (below).
GTAW: current 170 A, travel speed 4 mm/s; LAW: current 100 A, travel speed 4 mm/s and laser power 500 W.
5.4 CONCLUSIONS

In this chapter the arc manipulation capability of a low power Nd/YAG laser beam was examined experimentally and the results lead to the following conclusions.

1) The arc root can be fully coupled with the laser spot within a certain geometrical limitation, which makes possible to manipulate the arc. The maximum manipulation range depends on the arc and laser beam properties and on the welding conditions.

2) The interaction between the laser and the arc results in arc column constriction and current density redistribution, which was confirmed by photo-images and split-anode measurements. The increased current density within the arc can be regarded as another aspect of arc manipulation and control.

3) Arc manipulation by a laser beam gives the LAW a number of advantages over standard GTAW, such as improved possibilities for welding of thick-thin plate combinations, asymmetric edges and dissimilar materials.
REFERENCES


WELDING EFFICIENCY OF LASER-ASSISTED ARC WELDING

Welding efficiency is a very important aspect of welding. It consists of two parts: the energy transfer efficiency and the melting efficiency. The results of calorimetric measurements show that the laser-assisted arc welding (LAW) system has no extra advantage over the individual GTA welding and laser welding system as far as the energy transfer efficiency is concerned. Weld cross-section area measurements, however, indicate that the melting rate of LAW is considerably larger than the sum of the melting rates of GTA welding and laser welding. Analytical calculations prove that this synergic effect is caused by both constriction of the arc root and mutual heating.
6.1 INTRODUCTION

One of the advantages of the laser-arc hybrid welding system is its synergetic effect. This synergy is reflected by increased travel speed and/or enhanced weld penetration. However, due to the absence of a uniform definition of the welding efficiency in the case of a welding system composed of two heat sources, large disparities on the experimental data exist. Furthermore, little is known about hybrid systems using a Nd/YAG laser [6.1-6.6].

In this chapter, the welding efficiency of a 500 W Nd/YAG laser combined with a gas tungsten arc, laser-assisted arc welding (LAW), is evaluated. The evaluation is based on a definition of the welding efficiency, which consists of two parts: the energy transfer efficiency \( \eta_E \) and the melting efficiency \( \eta_m \), as expressed by the following equations:

\[
\eta_E = \frac{Q_i}{\int_0^1 (U \cdot I) \, dt + \int_0^1 W \, dt} \quad (6.1)
\]

\[
\eta_m = A \cdot \nu \cdot t \cdot (\int C_p dT + H_f) / Q_i \quad (6.2)
\]

where \( Q_i \) is the energy absorbed by the workpiece, \( I \) the arc current, \( U \) the arc voltage, \( W \) the laser power, \( C_p \) the heat capacity of the workpiece material, \( A \) the area of the transverse weld cross-section, \( \nu \) the travel speed, \( T \) the temperature, \( t \) the welding time and \( H_f \) the latent heat of fusion of the workpiece material.

For the determination of the energy transfer efficiency \( \eta_E \) and the melting efficiency \( \eta_m \), it is necessary to measure the amount of heat transferred from the welding source to the workpiece and the cross-section surface area of the weld. To this end, calorimetric measurements were conducted during GTA welding, laser welding and LAW, and of the welds obtained the transverse cross-section surfaces were determined.
Furthermore, theoretical calculations were performed of the surface area of the transverse cross-section of the weld using a modified analytical Rosenthal equation and the results of these calculations were compared with those of the experiments.

6.2 EXPERIMENTAL

The laser-assisted arc welding system used consists of a HAAS/506D Nd/YAG laser in combination with standard GTAW equipment. The technical details of the set-up and a schematic drawing are presented in Table 6.1 and Fig. 6.1 respectively. The workpiece material used in the experiments is mild steel Fe 360 in the form of plates having dimensions of $250 \times 50 \times 5$ mm for the weld cross-section measurements and $150 \times 50 \times 5$ mm (due to the size of the calorimeter) for the calorimetric measurements.

Table 6.1 Technical data of the set-up of laser-assisted arc welding.

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>mild steel Fe 360</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td>tungsten (2% th), $\varnothing$ 2.4 mm, 60 degree tip angle</td>
</tr>
<tr>
<td>Polarity</td>
<td>electrode negative (EN)</td>
</tr>
<tr>
<td>Electrode tip position</td>
<td>3 mm above workpiece and 2.5 mm from laser beam centre</td>
</tr>
<tr>
<td>Nd/YAG laser</td>
<td>500 W continuous wave</td>
</tr>
<tr>
<td></td>
<td>wavelength 1.06 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>focus spot diameter 0.3 mm ($7 \times 10^5$ W/cm$^2$)</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>argon (12 l/min)</td>
</tr>
</tbody>
</table>
The workpiece surface is cleaned with acetone before welding. For the weld cross-section measurements, samples are taken from the middle part of the weld. Samples are ground, polished and etched with Nital (5%). The surface area of the weld cross-sections is measured using an optical microscope (Leica Qwin) equipped with a digital analysis system.

A Seebeck envelope calorimeter is used for the calorimetric measurements. This calorimeter works on the gradient layer principle and produces a voltage output that is proportional to the flux through the walls during the time required for the weld sample and fixture to cool to room temperature. The calorimeter constant is obtained by averaging the results of three calibrations. The scatter of the results of the calibrations is shown to lie within 1%. A schematic drawing of the calorimetric measuring set-up is shown in Fig. 6.2. The measurement procedure consists of the following steps:

i) position the workpiece inside the calorimeter box and wait till the output signal of the calorimeter reaches equilibrium; ii) open the cover of the
calorimeter and perform the welding operation; iii) after welding immediately close the cover. The equipment and procedure provides high accuracy energy transfer measurements during the welding process [6.7].

Fig. 6.2 Schematic drawing of the calorimetric measurement set-up.

The welding process is controlled by a personal computer using the LabVIEW program. Arc current, arc voltage and welding time are recorded during the welding process. The calorimeter output signal is continuously measured during more than 10 hours by an oscilloscope till it reaches equilibrium.

During the experiments the laser power is kept constant at 500 W, whereas the arc current varies from 50 to 300 A. The welding head is maintained at a constant travel speed of 8 mm/s.
6.3 RESULTS AND DISCUSSION

6.3.1 ENERGY TRANSFER EFFICIENCY

To obtain quantitative information about the heat transfer from the heat source(s) to the workpiece during GTA welding, laser welding and laser-assisted arc welding, calorimetric measurements were conducted. Each welding experiment lasts about 10 seconds and was repeated twice for data accuracy. Integration of the arc power over the welding time and integration of the calorimeter output signal over the measuring time were performed using a LabVIEW program. The energy transfer efficiency was calculated using equation 6.1.

The results of the measurements are given in the histogram of Fig. 6.3. It appears that GTA welding at arc currents of 50 A, 100 A and 200 A has an efficiency of 78%, 81% and 82% respectively, laser welding at 500 W has an efficiency of 56% and laser-assisted arc welding has an efficiency of 65%, 72% and 76% at arc currents at 50, 100 and 200 A respectively.
Fig. 6.3  Energy transfer efficiency of GTA welding, laser welding and laser-assisted arc welding measured by means of a calorimeter.

It is believed that the energy loss of a welding arc is mainly caused by the radiation to the surrounding [6.8]. The fact that the arc length used in the present experiments is rather small (3 mm), implies that the energy loss by radiation is also small, which explains the relatively high efficiency values observed in the case of the GTA welding process.

The energy loss in the case of laser welding consists of two parts: workpiece surface reflection and energy absorption by the induced plasma [6.9]. In the case of LAW, the laser beam has to pass through the highly ionised arc column, which consequently results in energy loss to the plasma (see section 4.4.3).

In Fig. 6.4 the energy received by the workpiece is plotted as function of energy input from the heat sources. By comparison, the figure shows that the energy transferred to the workpiece in the LAW process is almost equal or even slightly smaller than the sum of the energy transferred in GTAW and laser welding separately.
Fig. 6.4 Energy received by the workpiece as a function of energy input for LAW (arc/laser) and for GTAW and laser welding together (arc+laser).

These results indicate that under the present experimental conditions the LAW process does not provide a benefit as far as the energy transfer efficiency is concerned.

6.3.2 MELTING EFFICIENCY

For the determination of the melting efficiency, bead-on-plate welds were produced by GTAW, laser welding and laser-assisted arc welding. Of each weld, transverse cross-sections were made and the weld surface areas were measured as described in section 6.2. Based on the net heat input measured by the calorimeter, the melting rate of each process was calculated according to equation 6.2. The physical properties used are listed in Table 6.2.
The results thus obtained are presented in Fig. 6.5. In the figure, the energy used for melting per unit time (melting rate) is plotted as function of the net heat input and it appears that the melting rate of LAW (arc/laser) is higher than the sum of the melting rates of GTAW and laser welding (arc+laser) in all tested situations.

![Graph showing energy used for melting per unit time (melting rate) as a function of heat input for LAW (arc/laser) and for GTAW and laser welding together (arc+laser).]

Fig. 6.5 Energy used for melting per unit time (melting rate) as a function of heat input for LAW (arc/laser) and for GTAW and laser welding together (arc+laser).

The weld bead depth/width ratio was also measured for each weld. Figure 6.6 shows the depth/width ratio of LAW and GTAW welds as a function of arc current. It can be seen that the D/W ratio for GTAW increases with increasing current and reaches a saturation level of about 25%, whereas the D/W ratio for LAW is significantly higher. However, the difference in D/W ratio becomes smaller when the arc current is higher than 250 A. The high value of the D/W ratio in the case of LAW at arc current 100 A is due to the fact that the arc power under these conditions is too low to produce any melting, as a
consequence of which the weld pool formation is still dominated by the 500 W laser beam.

![Graph showing D/W ratio of LAW and GTAW welds as a function of arc current.]

Fig. 6.6. The D/W ratio of LAW and GTAW welds as a function of arc current.

6.3.3 ANALYTICAL CALCULATIONS

The synergy of the LAW process can be qualitatively understood on the basis of first principles. First, it should be realise that the two energy sources that are combined in LAW have a mutual heating effect, which reduces the 'warm-up' energy for melting. Second, as shown by the anode-split experiments and photographic images, the arc is constricted in the case of LAW, which leads to a higher energy density.

In order to examine the influence of these two factors, calculations of the melting rate were performed using the Rosenthal equation in a modified form. The equation used is expressed below and takes into account that the heat source has a Gaussian distribution [6.10]:

- 104 -
\[
T = T_0 + \frac{q/v}{2\pi \lambda [t(t + t_0)]^{1/2}} \times \exp \left\{ -\frac{1}{4\alpha} \left[ \frac{(z + z_0)^2}{t} + \frac{y^2}{(t + t_0)} \right] \right\} 
\]
(6.3)

with \( t_0 = \frac{r_B^2}{4\alpha} \)

and \( z_0^2 = \frac{r_B}{\epsilon} \left( \frac{\pi \alpha r_B}{v} \right)^{1/2} \)

where \( q \) is the heat input, \( v \) the travel speed, \( \alpha \) the thermal diffusivity of the workpiece material, \( \lambda \) the thermal conductivity of the workpiece material, \( t \) the welding time, \( r_B \) the radius of the gaussian heat source, \( y \) and \( z \) the weld pool width and depth.

Calculations of the melting rate were conducted for GTA welding, laser welding and laser-assisted arc welding, using the same process parameters as used in the experiments. A LabVIEW computer program was designed for the calculation of the maximum weld pool depth \( z_m \) and width \( 2y_m \). The transverse cross-section surface area \( A \) of the weld was then calculated with the help of the equations:

\[
A = y_m \cdot z_m \cdot \pi/2 \quad (z_m > y_m) 
\]
(6.4)

\[
A = \pi r^2 - 2\arctg \frac{y_m \cdot r^2 - \sqrt{r^2 - y_m^2} \cdot y_m}{z_m} \quad (z_m \leq y_m \text{ and } r = \frac{z_m^2 + y_m^2}{2z_m}) 
\]
(6.5)

In the case of laser welding, the initial keyhole mode was observed, which produces a weld pool with a D/W ratio of 0.7. Therefore, in the calculation the laser heat source was split into two parts for better simulating the laser weld. One heat source is located on the workpiece surface and the other is located beneath the workpiece. The results of the calculation produce a molten area with a D/W ratio close to those obtained in the experiments. The arc radii were selected on the basis of photographic images (see Fig. 5.4). The arc radii \( r_B \) used are 1.2 and 1.6 mm for the situations with and without the presence of
laser radiation respectively. The mutual heating effect in the case of the laser-assisted arc weld was taken into account by adding the temperatures produced by the arc and the 500 W laser beam for all values of time.

The physical properties of the material used are listed in Table 6.2. In the calculations, the latent heat of fusion was compensated for all three processes in the same way as described in [6.10], whereas the enthalpy of evaporation was compensated when the temperature exceeded the evaporation point.

The results of the calculations are shown in Fig. 6.7. In this figure the calculated melting rate in the case of laser-assisted arc welding and the sum of the melting rates in the case of GTA welding and laser welding are plotted as a function of heat input. Comparison of Fig. 6.5 with Fig. 6.7 indicates that the results of the calculations agree reasonably well with those of the experiments. Apparently, arc constriction and mutual heating lead to a larger weld pool with a D/W ratio close to that found in real welding.

Table 6.2 Physical properties of the material used (Fe 360) [6.11].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal conductivity ( \lambda )</td>
<td>41 J/m/s/K</td>
</tr>
<tr>
<td>thermal diffusivity ( \alpha )</td>
<td>( 9.1 \times 10^{-6} ) m(^2)/s</td>
</tr>
<tr>
<td>latent heat of melting ( l_m )</td>
<td>250 kJ/kg</td>
</tr>
<tr>
<td>enthalpy of evaporation ( l_e )</td>
<td>6 MJ/kg</td>
</tr>
<tr>
<td>melting temperature ( T_m )</td>
<td>1790 K</td>
</tr>
<tr>
<td>evaporation temperature ( T_e )</td>
<td>3150 K</td>
</tr>
</tbody>
</table>
Fig. 6.7 Calculated melting rate as a function of heat input for LAW (arc/laser) and for GTAW and laser welding together (arc+laser).

It should be noted that the results of the calculations start to deviate from those of the experiments at high current. This is due to the fact that in the experiments the arc is more difficult to constrict with increasing current. This effect is significant at current values higher than 250 A.

6.3.4 INFLUENCE OF TORCH POSITION ON THE MELTING RATE

In the LAW experimental set-up the arc torch has a 30 degree inclination to normal due to geometrical restrictions. Under standard experimental conditions, the arc torch is behind the laser beam (torch is forward inclined). This is the position in which all previous experiments were carried out. However, it is also possible that the arc torch is in front of the laser beam (torch is backward inclined).
Experiments were conducted to examine the influence of the torch position on the melting rate and the shape and size of the weld pool. Welding runs were produced by the hybrid system with both torch positions for different values of arc current and of each weld obtained the transverse cross-section surface area and D/W ratio were determined.

It was found that the Lorentz force, which is one of the most important driving forces for liquid flow in the weld pool [6.12], is strongly influenced by this torch inclination. When the laser beam joins the arc, the laser-induced recoil force acts together with the Lorentz force.

Fig. 6.8 Schematic drawing of the influence of torch position on the fluid flow direction in the weld pool: (a) torch behind laser beam, (b) torch in front of laser beam.

In the case of the torch being behind the laser beam, it was found that the joined forces enhance the liquid downward flow resulting in a relatively deep weld pool as presented in Fig. 6.8a, whereas under the conditions with the arc being in front of the laser beam (torch is backward inclined), the joined forces
blow the weld pool liquid strongly backward resulting in a relatively shallow weld pool as shown in Fig. 6.8b. In the case of a high arc current, the weld bead quality with torch backward inclination becomes devastated: the joined Lorentz and recoil forces are so strong that the weld pool liquid separates from the solid base and forms a wave-like irregular weld bead, which results in a low melting rate as shown in Fig. 6.9.

![Graph showing cross-section area vs. arc current](image)

**Fig. 6.9.** Surface area of the cross-section of welds produced by LAW with different torch positions as function of arc current.

However, in case of a low arc current, the arc can only form a small weld pool, and under these conditions the torch being in front of the laser beam produces both a higher melting efficiency and a higher weld pool D/W ratio than when the torch is behind the laser beam. The results indicate that the liquid backward flow (Fig. 6.8b) enhances the melting efficiency in the case of a small weld pool. It should also be kept in mind that now the laser power is the dominating energy source, the arc in front of the laser beam preheats the workpiece and may effectively increase the laser absorption efficiency.
6.4 CONCLUSIONS

In this chapter, the energy transfer efficiency and the melting efficiency of laser-assisted arc welding are addressed experimentally and theoretically. The following conclusions based on the obtained results are drawn.

1) The energy transferred to the workpiece in the case of laser-assisted arc welding is almost the same as the sum of the energies transferred in the case of GTA welding and laser welding.

2) Under the tested conditions, the melting rate of laser-assisted arc welding is considerably larger than the sum of the melting rates of GTA welding and laser welding.

3) Analytical calculations show that the synergic melting effect of LAW is due to arc constriction and mutual heating of the two energy sources.

4) Torch inclination has an important influence on the melting rate due to flow direction of the liquid metal in the weld pool. Torch backward inclination (torch in front of laser beam) favours melting under low arc current conditions, whereas the torch forward inclination (torch behind laser beam) produces a higher melting rate under high arc current conditions.
REFERENCES


THERMAL AND MICROSTRUCTURAL CHARACTERISTICS OF LASER-ASSISTED ARC WELDING

In laser-assisted arc welding use is made of a combination of two heat sources: the welding arc and a low-power laser beam. Welding experiments were carried out using a GTA welding arc in combination with a 500 W Nd/YAG laser and with mild steel as the workpiece material. It was found that in comparison with conventional GTA welding, laser-assisted arc welding leads to a smaller weld bead width and to a finer weld grain structure. These effects are due to heat source modification and increase in heating and cooling rate caused by the arc-laser interaction. Apart from the experiments, a FEM model was developed, which describes the thermal and microstructural characteristics of the laser-assisted arc welding process. It appears that good agreement exists between the model and the experimental results.
7.1 INTRODUCTION

In the previous chapters it was shown that laser radiation has a beneficial effect on the properties of the arc welding process. In fact, it appears that combining a laser beam with a welding arc facilitates arc ignition, leads to stabilisation of the arc, enables the possibility of arc manipulation and improves the welding efficiency. This has resulted in the development of a new hybrid welding process in which a laser and an arc are combined [7.1-7.9].

In spite of the research carried out thus far, little is known about the thermal characteristics of the hybrid process and its influence on the weld microstructure.

This chapter deals with the thermal and microstructural characteristics of laser-assisted arc welding (LAW). Experiments were carried out using a 500 W Nd/YAG laser in combination with GTAW equipment. In addition, a FEM model was developed, which describes the thermal characteristics of the laser-assisted arc welding process.

7.2 EXPERIMENTAL SET-UP

The laser-assisted arc welding system used in this study consists of a HAAS 506D laser (Nd/YAG) in combination with standard GTA welding equipment. A schematic drawing of the set-up is shown in Fig. 7.1. Detailed information about the laser beam and the GTA welding equipment is given in Table 7.1.

Bead-on-plate welding was carried out using two types of steel: low carbon steel FeP04 and medium carbon steel C45 in the form of plates having dimensions of 250×50×1 mm. The chemical compositions of the steels are listed in Table 7.2. Before welding, the surface of the plates was cleaned with acetone. After welding, transverse cross-sections were made of each weld and
these cross-sections were ground, polished and etched with 2% nital for microstructural study.

Fig. 7.1 Schematic drawing of the laser-assisted arc welding set-up.

Table 7.1 Technical data of the laser-assisted arc welding set-up.

<table>
<thead>
<tr>
<th>GTA welding unit</th>
<th>Laser beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode: tungsten + 2% Th</td>
<td>Nd/YAG 500 W, continuous wave</td>
</tr>
<tr>
<td>electrode diameter: Ø 2.4 mm</td>
<td>wavelength: 1.06 µm</td>
</tr>
<tr>
<td>torch inclination: 30° to normal</td>
<td>power density: 7x10^5 W/cm²</td>
</tr>
<tr>
<td>polarity: DCEN</td>
<td></td>
</tr>
<tr>
<td>shielding gas: argon</td>
<td></td>
</tr>
<tr>
<td>flow rate: 12 l/min</td>
<td></td>
</tr>
</tbody>
</table>
Table 7.2 Chemical composition (wt %) of steel FeP04 and steel C45.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeP04</td>
<td>0.047</td>
<td>0.227</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.013</td>
</tr>
<tr>
<td>C45</td>
<td>0.42-0.50</td>
<td>0.5-0.8</td>
<td>0</td>
<td>0</td>
<td>&lt;0.045</td>
<td>&lt;0.045</td>
</tr>
</tbody>
</table>

7.3 FEM CALCULATION OF THE THERMAL CYCLE

In addition to the experiments, FEM calculations were carried out of the thermal cycle experienced by the workpiece during welding. The calculations were performed using the commercial FEM package MARC Mentat and were based on the equation:

$$\rho C_p \frac{dT}{dt} - \nabla (k \nabla T) = \frac{dQ}{dt}$$

(7.1)

where $\rho$ is the density of the metal, $C_p$ the specific heat of the workpiece material, $T$ the temperature, $t$ the time, $k$ the thermal conductivity and $\frac{dQ}{dt}$ the production of heat per unit time. The heat input of the arc and the laser were assumed to have a Gaussian distribution, which was achieved by using the Flux sub-routine in the program. The arc energy input was simulated using a surface flux, whereas the laser beam energy input was simulated using a volume flux through the entire workpiece thickness.

For affordable computer capability, the workpiece was assumed to travel at a constant speed towards the heat source using a velocity term. The mesh size was chosen to depend on the position and was smallest (0.047 mm) around the heat source. The total element number in the model was 12944. The temperature dependent physical properties of the steels used in the calculations were taken from existing literature [7.10, 7.11].
The calculation was conducted in a transient heat transfer mode. The welding parameters used in the calculation were the same as in the experiments. The arc root radius and energy transfer efficiencies used are listed in Table 7.3. Fluid flow in the weld pool was not taken into account due to the limitation of the program.

Table 7.3 Arc root radius and energy transfer rate of GTAW and LAW.

<table>
<thead>
<tr>
<th>Arc current (A)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>arc root radius in GTAW (mm)</td>
<td>2.67</td>
<td>3</td>
<td>3.5</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>arc root radius in LAW(mm)</td>
<td>2</td>
<td>2.25</td>
<td>2.6</td>
<td>3</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>energy transfer efficiency of arc</td>
<td>0.7</td>
<td>0.75</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>energy transfer efficiency of laser</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

7.4 RESULTS AND DISCUSSION

7.4.1 THERMAL BEHAVIOUR

To be able to assess the difference in thermal behaviour of the conventional GTA welding process and the laser-assisted arc welding process, process windows were determined for the two processes using plates of both steel FeP04 and steel C45 as workpiece. This was done by carrying out welding experiments with different arc powers (between 250 and 2000 W) without and in combination with a constant laser power (500 W). For each power combination the travel speed was adjusted in such a way that a fully penetrated weld was formed, with a backside width of 1~1.5 mm.

The results obtained are presented in Table 7.4. In the table, parameter sets (arc current, arc voltage, and travel speed) are listed together with the corresponding values of the energy input, calculated on basis of the efficiencies given in Table 7.3.
### Table 7.4 Experimental parameter matrix.

<table>
<thead>
<tr>
<th>Material</th>
<th>Process</th>
<th>Laser power (W)</th>
<th>Arc current (A)</th>
<th>Arc voltage (V)</th>
<th>Arc power (W)</th>
<th>Total power (W)</th>
<th>Travel speed (mm/s)</th>
<th>Energy input (J/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FePO4</td>
<td>GTAW</td>
<td>-</td>
<td>50</td>
<td>10.2</td>
<td>510</td>
<td>510</td>
<td>5.5</td>
<td>70</td>
</tr>
<tr>
<td>FePO4</td>
<td>GTAW</td>
<td>-</td>
<td>75</td>
<td>10.2</td>
<td>765</td>
<td>765</td>
<td>9</td>
<td>68</td>
</tr>
<tr>
<td>FePO4</td>
<td>GTAW</td>
<td>-</td>
<td>100</td>
<td>10.7</td>
<td>1070</td>
<td>1070</td>
<td>13</td>
<td>66</td>
</tr>
<tr>
<td>FePO4</td>
<td>GTAW</td>
<td>-</td>
<td>125</td>
<td>11</td>
<td>1375</td>
<td>1375</td>
<td>17</td>
<td>65</td>
</tr>
<tr>
<td>FePO4</td>
<td>GTAW</td>
<td>-</td>
<td>150</td>
<td>10.3</td>
<td>1545</td>
<td>1545</td>
<td>22</td>
<td>56</td>
</tr>
<tr>
<td>FePO4</td>
<td>GTAW</td>
<td>-</td>
<td>175</td>
<td>10.5</td>
<td>1837</td>
<td>1837</td>
<td>26</td>
<td>57</td>
</tr>
<tr>
<td>FePO4</td>
<td>LAW 500</td>
<td>25</td>
<td>10.3</td>
<td>257</td>
<td>757</td>
<td>10</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>FePO4</td>
<td>LAW 500</td>
<td>50</td>
<td>10.7</td>
<td>535</td>
<td>1035</td>
<td>14</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>FePO4</td>
<td>LAW 500</td>
<td>75</td>
<td>9.5</td>
<td>712</td>
<td>1212</td>
<td>20</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>FePO4</td>
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<tr>
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<td>1287</td>
<td>1787</td>
<td>29</td>
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</tr>
</tbody>
</table>
It can be seen that both in the case of GTA welding and laser-assisted arc welding, the welding efficiency increases (the required energy input decreases) with increasing arc current. The table also clearly demonstrates the positive synergic effect of the laser on the welding arc. In fact, considerably less energy is required for the formation of a good weld in the case of laser-assisted arc welding than in the case of GTA welding. These results are in good agreement with those presented in Chapter 6.

7.4.2 WELD BEAD PROFILE

The fact that in the case of laser-assisted arc welding less heat is required to form a good weld than in the case of GTA welding implies that the weld width will be smaller. This is indeed the case as illustrated in Fig. 7.2. In this figure transverse cross-sections are presented of welds in steel FeP04 produced by GTA welding and by laser-assisted arc welding.

Fig. 7.2 Cross-sections of welds in steel FeP04 obtained by GTA welding at travel speed of 13 mm/s (above) and LAW at travel speed of 14 mm/s (below).
Apart from the geometric difference, it also appears that laser-assisted arc welds are considerably more regular, both on the top side and on the backside than GTA welds. This becomes particularly apparent at high travel speeds. The stabilising influence of the laser beam on the behaviour of the arc is due to fixation of the arc by the laser as discussed in Chapter 5.

Parallel to the welding experiments, FEM calculations of the temperature profiles in the workpiece were performed using the same process parameters as used in the experiments. An example of the results obtained is shown in Fig. 7.3.

![Diagram of weld pool centre with temperatures 900 °C and 1500 °C](image)

**Fig. 7.3** Cross-section of weld in steel FeP04 obtained by LAW at travel speed of 20 mm/s with corresponding temperature profile obtained by FEM simulation.

The figure shows that, although fluid flow is not taken into account in the calculation, the temperature profiles of the weld metal and the heat-affected
zone obtained by calculation agree well with those reflected by the cross-
section.

7.4.3 WELD MICROSTRUCTURE

When considering the weld cross-sections presented in Fig. 7.2, it can be seen that apart from their size, the overall appearance of the two welds is similar: in both welds a clear distinction can be made between the heat-affected zone and the weld metal. However, on a smaller scale, differences in the structure of both the heat-affected zone and the weld metal are revealed.

In Fig. 7.4 a high-magnification image of part of the heat-affected zone of both welds is shown. It can be seen that less grain growth has occurred in the heat-affected zone of the laser-assisted welds than in the heat-affected zone of the GTA welds.

A measure of grain growth in the heat-affected zone of a weld is given by the equation [7.12]:

\[ I = \int_0^\infty \exp \left\{ -\frac{Q}{RT(t)} \right\} dt \]  

(7.2)

where I is the kinetic strength integral for grain growth over the thermal cycle (which is proportional to the change in the square of the grain size), Q the activation energy for self-diffusion, R the gas constant and T(t) the time dependent temperature. Fig. 7.5 shows the calculated temperature-time cycle in the heat-affected zone close to the fusion line for both GTA welding and laser-assisted arc welding. The part of the cycle during which grain growth occurs is indicated as the time \( \Delta t \). It can be seen that \( \Delta t \) (GTAW) > \( \Delta t \) (LAW), which qualitatively explains the different grain growth in both welds.
Fig. 7.4  Microstructure of HAZ of welds in steel FeP04 obtained by GTAW at travel speed of 22 mm/s (above) and LAW at travel speed of 20 mm/s (below).
Fig. 7.5 Temperature-time cycles obtained by FEM simulation for welds in steel FeP04 obtained by GTAW at travel speed of 22 mm/s and LAW at travel speed of 20 mm/s.

In Fig. 7.6 a high-magnification image of part of the weld metal of both welds is shown. It can be seen that during laser-assisted arc welding long and narrow grains are formed, which are strongly oriented towards the weld centre line, whereas in the case of GTA welding equi-axed grains are formed.

The observed difference in grain growth behaviour is directly related to the difference in temperature gradient during the solidification: the larger the temperature gradient, the larger the driving force for grain growth towards the weld centre and the stronger the orientation of the grains. This is confirmed by the results of FEM calculations, which are presented in Fig. 7.7. This figure shows that the temperature gradient during formation of the laser-assisted arc weld is considerably larger than that during the formation of the GTA weld.
Fig. 7.6  Microstructure of the weld metal of welds in steel FeP04 obtained by GTAW at travel speed of 22 mm/s (above) and LAW at travel speed of 20 mm/s (below).
Fig. 7.7 Temperature gradient obtained by FEM simulation for welds in steel FeP04 obtained by GTAW at travel speed of 22 mm/s and LAW at travel speed of 20 mm/s.

7.4.4 PHASE TRANSFORMATION

During cooling down to room temperature, the weld (weld metal and HAZ) undergoes one or more phase transformations. The amounts and distribution of the final phases depend on the cooling rate, which for the steels under consideration (FeP04 and C45) can be represented by the cooling time between 800 and 500 °C (∆t_{8/5}).

Microstructural examinations together with micro-hardness tests show that both in the case of GTA welding and in the case of laser-assisted arc welding of steel FeP04, the final phases in the weld are ferrite with pearlite at the grain boundaries.

In the case of the C45 steel, a fully martensitic structure is observed in all laser-assisted arc welds, whereas the GTA welds produced at small travel speed
(4.5 mm/s) contain bainite, ferrite and cementite. When increasing the travel speed, the morphology of the GTA welds gradually changes to a mixture of martensite, bainite, ferrite and retained austenite, whereas at high travel speed only martensite with some retained austenite is formed.

It appears that the observed transformations can be well understood by considering the calculated cooling rates of the welds, in combination with the CCT curves of the steels.

In fact, the results of the experiments and the FEM calculations indicate that the cooling rate in the case of laser-assisted arc welding, even at very low current, is much smaller than that in the case of laser welding, but higher than that in the case of GTA welding, which increases the possibility of obtaining hardened phases in the weld. For instance in the weld of steel C45, in the case of laser-assisted arc welding at a travel speed of 9 mm/s the cooling rate has a value of 130 °C/s, whereas in the case of GTA welding at a travel speed of 4.5 mm/s the cooling rate is about 52 °C/s and in the case of laser welding at a travel speed of 8 mm/s the cooling rate is about 400 °C/s. The obtained results are in quantitative agreement with the CCT-diagram of steel C45 presented in Fig. 7.8 [7.13] and with the results of micro-hardness test shown in Fig. 7.9.

FEM calculations also show that in the case of LAW it is possible to achieve post-heating effects by separating the arc and the laser beam over a certain distance. Under these special conditions the cooling rate of the weld can be modified to be even lower than that in the case of GTA welding, whilst the weld maintains the shape of a laser weld. An example of FEM calculations on the thermal history of the post-heating effect is given in Fig. 7.10.
Ck 45 0.44% C - 0.66% Mn (SAE 1042)
Composition: 0.44% C - 0.66% Mn - 0.22% Si - 0.012% P - 0.029% S - 0.15% Cr - 0.02% V Austenitized at 880°C (1616°F)

Austenitierungstemperatur 880 °C
(Heizdauer 3 min) aufgeheizt in 2 min

\[ \text{Ac}_1 = 735°C \]
\[ \text{Ac}_3 = 785°C \]
\[ M_s = 380°C \]

Fig. 7.8 Cooling rates in a modified CCT diagram of steel C45 [7.13].
Fig. 7.9 Micro-hardness (load 100 g) as a function of distance from weld centre of welds in steel C45 obtained by GTA welding at travel speed of 4.5 mm/s (above), by LAW at travel speed of 9 mm/s (middle) and by laser welding at travel speed of 8 mm/s (below).
Fig. 7.10 Temperature-time cycles obtained by FEM simulation for welds in steel C45 produced by 50 A GTA welding at travel speed of 4.5 mm/s, by 500 W laser welding and LAW (post-heating) at travel speed of 8 mm/s.

7.5 CONCLUSIONS

This chapter deals with the thermal characteristics of the laser-assisted arc welding system and its influence on the weld microstructure. The results obtained lead to the following conclusions.

1) The laser has a positive synergic effect on the welding arc: less energy is required for the formation of a good weld in the case of laser-assisted arc welding than in the case of GTA welding. This effect is due to constriction of the arc by the laser (more concentrated heat source).
2) As a consequence of the synergic arc–laser interaction, the weld width is smaller in the case of laser-assisted arc welding than in the case of GTA welding.

3) Due to the shorter duration of the thermal cycle, less grain growth takes place in the heat-affected zone of laser-assisted arc welds than in the heat-affected zone of GTA welds.

4) In the case of laser-assisted arc welding, the weld metal grains have a strong orientation towards the weld centre, due to the relatively large temperature gradient at the solidification front.

5) The thermal cycle of the laser-assisted arc welding process can be tuned by modifying the laser-arc power combination. This provides good possibilities to adapt the cooling rate and, hence, the weld microstructure.
REFERENCES


**SUMMARY**

**ND/YAG LASER-ASSISTED ARC WELDING**

The objective of the study presented in this thesis is to obtain fundamental understanding of the interaction between the Nd/YAG laser beam and the welding arc and to explore the possible industrial applications of this new hybrid welding system.

After a general introduction, the thesis continues in Chapter 2 with the study of the Nd/YAG laser-induced plasma plume and the weld bead generation. The results of experiments conducted under standard conditions are presented and attention is given to the influence of the shielding gas, the workpiece material, the laser power and the laser energy density. The experiments show that when a laser beam impinges on a metal surface optical energy is absorbed, which locally leads to melting and evaporation of the metal. The evaporated metal is pushed upwards forming the so-called laser-induced plasma plume. The laser energy density is characterised by a threshold value, below which a moderate and smooth plume and a semi-spherical weld bead are formed (heat-conduction mode); above this threshold value, intensive and pulsed evaporation occurs, resulting in a large plasma plume and a weld bead with a high depth/width ratio (keyhole mode). The shielding gas has a significant influence on plume and bead formation. Helium as the shielding gas results in a plume about half the size of that of argon. In open air, the surface oxidation dramatically increases the laser energy absorption, which leads to an increase of plume size and weld bead depth. The influence of travel speed on plume generation is insignificant within the tested range and the weld bead depth/width ratio remains unchanged. Experiments show that in the case of mild steel as workpiece material a 500 W
Nd/YAG laser has a 56% energy transfer efficiency and a 29% melting efficiency at a travel speed of 8 mm/s and with argon as the shielding gas.

Chapter 2 lays the foundation for the laser-arc interaction discussed in the following chapters. It appears that the Nd/YAG laser-induced plasma plume is distinctively different from the welding arc plasma. In Chapter 3, it is shown that the breakdown voltage required for ignition of the welding arc is significantly reduced by the presence of a laser-induced plasma plume. Under electrode positive conditions (the electrode is connected to the positive pole of the DC power source), the observed reduction of the breakdown voltage is caused by stimulated thermionic emission. Under electrode negative conditions (the electrode is connected to the negative pole of the DC power source), enhanced field emission also plays a role. The breakdown voltage increases with increasing laser energy density under the tested conditions. This is due to the higher pressure generated inside the plume by the severe evaporation and the appearance of strong fluctuations in the current and spatter at high laser energy. The breakdown voltage depends on the type of the shielding gas used. It appears that argon leads to a lower breakdown potential than helium. Air hampers the current/ionisation development between the electrodes by electron capture and oxidation of the metal.

The interaction of the laser beam with the arc plasma is discussed in Chapters 4 and 5. In Chapter 4 the attention is focused on the influence of laser radiation on arc stability. An arc stabilisation mechanism is proposed and this mechanism is validated by measuring the arc absorption of the laser beam energy and by spectroscopic analysis of the plasma composition. The results show that the welding arc can be effectively stabilised by a Nd/YAG laser beam of moderate power (500 W). About 0.28% and 0.7% of the 500 W laser beam energy is absorbed when the laser passes through an arc of 50 A and 100 A respectively. The spectroscopic measurements show that the metal atoms
generated by the evaporation replace part of the atoms of the shielding gas and dominate the ionisation due to their lower ionisation potential. The metal-argon mixture plasma forms a stable arc root and arc column channel.

Chapter 5 deals with arc manipulation by means of a laser beam. It appears that the arc root can be fully coupled with the laser spot within a certain geometrical limitation. The maximum manipulation distance depends on the arc and laser beam properties and the welding conditions. The arc column constriction and current density redistribution due to the presence of the laser beam is confirmed by photography and split-anode measurements. The increased current density within the arc can be regarded as another aspect of arc manipulation. Arc manipulation by a laser beam gives laser-assisted arc welding (LAW) a number of advantages over standard GTAW. Typical application examples are the improved possibilities for welding of thick-thin plate combinations, edge welding and welding of dissimilar materials.

The welding efficiency of LAW is addressed in Chapter 6. The energy transfer efficiency as well as the melting rate of GTA welding, laser welding and laser-assisted arc welding are compared experimentally and theoretically. Under the tested conditions, the energy transferred to the workpiece in the case of laser-assisted arc welding is about equal to the sum of the energies transferred in the case of GTA welding and laser welding. However, the melting rate of laser-assisted arc welding is considerably larger than the sum of the melting rates of GTA welding and laser welding. The synergic melting effect of LAW is due to arc constriction and mutual heating of the two energy sources as confirmed by analytical calculations.

Last but not the least, the thermal and microstructural characteristics of the new hybrid welding system are presented in Chapter 7. On the basis of FEM calculations and experimental work it is shown that laser-assisted arc welding has specific advantages over conventional GTA welding, in particular as far as
weld bead profile and microstructure are concerned. As a consequence of the synergic arc-laser interaction, the weld width is smaller in the case of laser-assisted arc welding than in the case of GTA welding. Due to the shorter duration of the thermal cycle, less grain growth takes place in the heat-affected zone of laser-assisted arc welds. In the case of LAW the weld metal grains have a strong orientation towards the weld centre, due to the relatively large temperature gradient at the solidification front. It was also found that the thermal cycle of the laser-assisted arc welding process could be tuned by modifying the laser-arc power combination. This provides good possibilities to adapt the cooling rate and, hence, the weld microstructure in the case of LAW.

Bin HU
Delft, May 2002
SAMENVATTING

ND/YAG LASER-ONDERSTEUNDE TIG LASSEN

Het doel van het in dit proefschrift beschreven onderzoek is het verkrijgen van fundamenteel inzicht in de interactie tussen een Nd/YAG laserbundel en een lasboog en het verkennen van mogelijke industriële toepassingen van dit nieuwe hybride lasysteem.

Na een algemene inleiding, wordt in hoofdstuk 2 de door een Nd/YAG lasergegenereerde plasma-pluim en de vorming van het lasbad besproken. De onderstaande condities verkregen resultaten worden gepresenteerd waarbij aandacht wordt besteed aan de invloed van de samenstelling van het beschermgas, het proefstukmateriaal, het laservermogen en de energiedichtheid van de laser. De experimenten tonen aan dat wanneer een laserbundel een metaaloppervlak treft, optische energie wordt geabsorbeerd, hetgeen lokaal leidt tot smelten en verdampen van metaal. Het verdampde metaal wordt omhoog gestuwd en vormt op die manier de zogenaamde laser-geïnduceerde plasma-pluim. Als de energiedichtheid van de laser onder een bepaalde drempelwaarde ligt zal de pluim homogen van vorm zijn en wordt een bolvormig lasbad gevormd (warmte-geleidingsmode). Boven de drempelwaarde vindt er intensieve en gepulste verdamping plaats, hetgeen leidt tot een grote plasma-pluim en een lasbad met een grote diepte/breedte verhouding (sleutelgatmode). Het beschermgas heeft een significante invloed op de pluim en de vorming van het lasbad. Helium als beschermgas leidt tot een pluim die ongeveer half zo groot is als die in het geval van argon. Onder atmosferische omstandigheden zorgt de oxidatie van het oppervlak voor een drastische toename van de absorptie van de laserenergie, hetgeen leidt tot een grotere pluim en een grotere lasbaddiepte. De invloed van de lassnelheid op de
pluimontwikkeling is verwaarloosbaar binnen de proefomstandigheden en ook de diepte/breedte verhouding van het lasbad hangt nuwalijs af van de lassnelheid. Experimenten uitgevoerd op een stalen proefstuk tonen aan dat een Nd/YAG laser met een vermogen van 500 W een thermisch rendement heeft van 56 % en een smeltrendement van 29 %, bij een lassnelheid van 8 mm/s en argon als beschermgas.

Hoofdstuk 2 legt het fundament voor de discussie over de laser-boog interactie die aan de orde komt in de volgende hoofdstukken. Het blijkt dat de Nd/YAG laser-geïnduceerde plasma-pluim wezenlijk verschilt van het boogplasma. In hoofdstuk 3 wordt aangetoond dat de doorslagspanning die nodig is voor ontsteking van de lasboog aanzienlijk wordt verlaagd door de aanwezigheid van een laser-geïnduceerde plasma-pluim. In het geval dat de elektrode verbonden is met de positieve pool van de gelijkstroombron (elektrode fungeert als anode), wordt de waargenomen afname van de doorslagspanning veroorzaakt door gestimuleerde thermische emissie. Als de elektrode als kathode fungeert speelt tevens veldemissie een rol. De doorslagspanning neemt toe met de vermogensdichtheid van de laserbundel onder de proefomstandigheden. Dit komt door de hogere druk die gegenereerd wordt in de pluim ten gevolge van de sterke verdamping en de grote fluctuaties in de stroom bij hoog bundelvermogen. De doorslagspanning hangt ook af van de chemische samenstelling van het gebruikte beschermgas. Het blijkt dat argon leidt tot een lagere doorslagspanning dan helium. Lucht belemmert de ionisatie en de ontwikkeling van stroom tussen de elektrodes doordat het elektronen afvangt en door oxidatie van het metaalloppervlak.

De interactie tussen de laserbundel en het boogplasma is het onderwerp van de hoofdstukken 4 en 5. In hoofdstuk 4 ligt de nadruk op het onderzoeken van de invloed van de laserstraling op de stabiliteit van de lasboog. Een mechanisme voor boogstabilisatie wordt voorgesteld en gevalideerd door het
meten van de absorptie van de laserbundelenergie door de lasboog en door spectroscopische analyse van de plasmasamenstelling. De resultaten laten zien dat de lasboog effectief gestabiliseerd kan worden door een Nd/YAG laserbundel met een bundelvermogen van 500 W. Ongeveer 0,28 % en 0,7 % van de 500 W laserenergie wordt geabsorbeerd door een lasboog van respectievelijk 50 A en 100 A. De spectroscopische analyse toont aan dat de metaalatomen die door de verdamping worden gegenereerd voor een deel de atomen in het beschermgas vervangen en vanwege hun lagere ionisatiepotentiaal het ionisatieproces domineren. Het metaal-argon plasma mengsel vormt een stabiele anodevlak en een stabiele boogzuil.

In hoofdstuk 5 worden de resultaten gepresenteerd van lasboogmanipulatie door middel van een laserbundel. Het blijkt dat de anodevlak binnen zekere geometrische grenzen volledig gekoppeld kan worden met de laser. De maximale afstand waarover manipulatie mogelijk is hangt af van de eigenschappen van de boog en de laserbundel, en van de lasomstandigheden. De contractie van de boogzuil en de hervordering van de stroomdichtheid door de laserbundel is onderzocht met behulp van fotografie en experimenten met een gesplitste anode. De toegenomen stroomdichtheid in de boog kan worden beschouwd als een ander aspect van de lasboogmanipulatie.


Het rendement van LOTL wordt besproken in hoofdstuk 6. Zowel het thermisch rendement als het smeltrendement van TIG-lassen, laserlassen en LOTL worden experimenteel en theoretisch vergeleken. De energie die naar het werkstuk wordt getransporteerd in het geval van LOTL blijkt ongeveer gelijk te
zijn aan de som van de getransporteerde energiën in het geval van TIG-lassen en laserlassen afzonderlijk. Daarentegen is de smeltsnelheid van LOTL aanmerkelijk groter dan de som van de smeltsnelheden van TIG-lassen en laserlassen. Het synergetisch smelteffect van LOTL wordt veroorzaakt door de boogcontractie en de onderlinge verwarming van de twee energiebronnen, hetgeen wordt bevestigd door analytische berekeningen.


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