

# Optimization of Nd:YAG Laser Welding of Magnesium

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Magnesium alloys have attracted the interest of modern manufacturing industry owing to their higher strength-to-weight ratios and heat conductivity than other alloys. Laser welding will be an important joining technique for magnesium alloys with their increasing applications in aerospace, aircraft, automotive, electronics and other industries. The Nd:YAG laser beam has a reputation for rapid, precise and easy operation in welding of magnesium. In this study the use of an Nd:YAG laser for thin plate magnesium alloy butt welding was optimized. Some important laser processing parameters and their effects on weld quality are discussed. The microstructure and metallurgical defects encountered in laser welding of magnesium alloys, such as porosity, welding cross sections geometry etc. were determined by optic microscopy. The welding parameters (the shielding gas, convey speed of work piece, laser focal position, pulse frequency, and pulse waveform governing the laser beam in thin plate butt welding were evaluated by gometric parameters.

**Keywords:** Nd:YAG laser, welding, material processing

## 1. Introduction

Magnesium is one of the most abundant elements on the Earth's surface. Magnesium is an extremely light metal having excellent specific strength, excellent sound damping capabilities, good castability, hot formability, excellent machinability, good electromagnetic interference shielding, and recyclability [1]

The properties of magnesium are very suitable for automotive industry in order to achieve remarkable vehicle weight reduction which improves the automotive fuel efficiency. Metal alloys and polymers are already being used to reduce weight significantly, but remarkable reductions could be achieved by using low-density magnesium (Mg) and its alloys in large proportions. Magnesium is an attractive material for automotive use, primarily because of its light weight 36% lighter per unit volume than Al and 78% lighter than iron (Fe). Also alloyed Mg has the highest strength-to-weight ratio of all structural metals. Because of these advantages Mg and its alloys become to be one of the most attractive materials in automotive industry compared to steel and aluminum materials [2].

Although the cost and supplying amount is not suitable, the use of magnesium in automotive applications is growing. The average magnesium content in 2002 model cars was reported as 4 kg, compared with 3.8 kg for the previous model year [3]. This increase is mainly due to the use of magnesium in many parts of the automobile like, steering wheel armatures, teering column jackets, and steering column/pedal bracket supports etc. Magnesium parts are generally joined to other mechanical parts by means of laser welding. Magnesium and its alloys also find many applications in the aerospace industry, in gearbox casings, oil

sumps, helicopter turbines, aircraft wheels, seat structures etc. [3]

The high demand in magnesium applications makes the welding of magnesium an attractive subject for researchers and manufacturers. Compared to other welding techniques laser welding has numerous advantages such as narrow affected zone, low contamination risk by unwanted components during the welding, good quality of joints, lowest porosity in the fusion zone, low heat affected zone (HAZ) and no cracks, easy of automation and high production speed etc. [4].

There are many laser welding parameters affecting the welding quality. Laser power, welding speed, focal position, shielding gas flow, laser pulse frequency etc. are considered as the base laser welding parameters and should be optimized for high welding quality [5]. Unsuitable welding parameters results in many defects such as an unstable weld pool, substantial spatter, tendency to drop-through for large weld pools, sag of the weld pool, undercut, porous oxide inclusions, loss of alloying elements, liquation and solidification cracking [1]. On the other hand in order to achieve optimum welding in production both welding quality and productivity should be optimized.

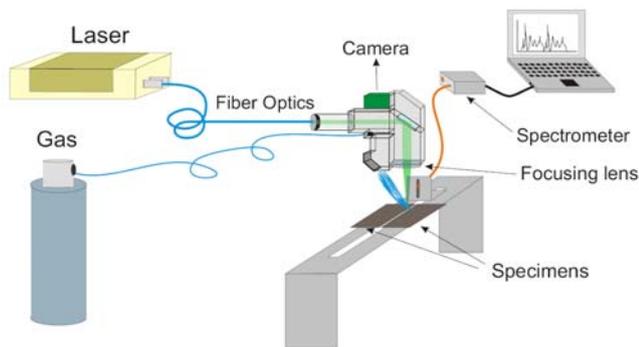
Leong investigated the welding of magnesium alloys using both CO<sub>2</sub> and pulsed Nd:YAG lasers, and illustrated the difficulties of CO<sub>2</sub> welding. He concluded that Nd:YAG laser was more suitable for Mg alloy welding [6].

In continuous pulse type lasers it is easier to control the laser welding parameters. On the other hand the ability of optimizing welding quality according to material and proc-

essing condition is limited. Pulsed lasers have a great flexibility to optimize the welding parameter. The precision between the designed and achieved laser pulses also affects the welding quality. There is limited study on laser welding of magnesium alloys in the literature [7]. In this study we follow the optimized laser welding parameters, which are given in literature. The materials were welded with systematically changed parameters and their effects on welding quality at the cross section of the material were investigated. During the welding studies the laser beam profile, laser energy, pulse frequency, etc. are measured in order to be sure of the realized working parameters.

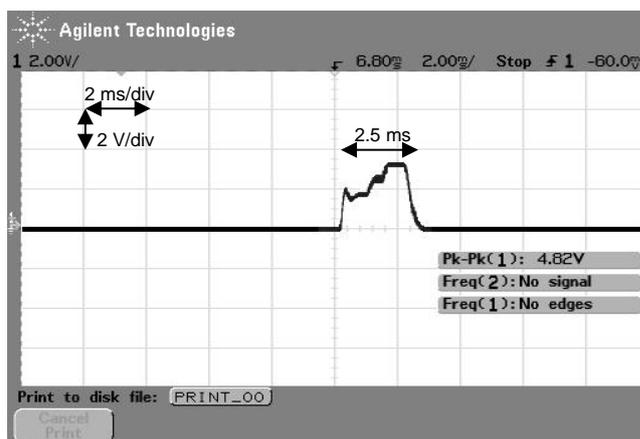
**2. Experimental laser welding process**

In this study the GSI lumonics JK700TR Series Laser (Class 4) system is used. The JK700TR Series of laser is an Nd:YAG laser that has 0.1ms to 20 ms pulse length and 500 Hz repetition rate. The average power that can be obtained is 600 Watt. Laser output power is delivered via a 600 μm radius fiber optic cable to the focus head at the workstation for processing. Figure 1 shows the experimental setup. The laser beam is focused on magnesium plates using 200mm focal length with 2 inch lens. The spot size on the plates was ≈0.5 mm. The workpieces, placed in a cabin, are moved using an x-y translation stages. The laser focusing head is moved using translation stages on z-direction to find the best focusing position. The shielding gas is spread trough a nozzle on plates to prevent the welding from oxidation. The pulse duration and waveform are measured using a photodiode. The emission spectrum from the welding process is recorded using a VIS-NIR spectrometer (Newport OSM-100 Spectrometer). The laser power is measured for each process using a power meter.



**Fig.1** The experimental setup.

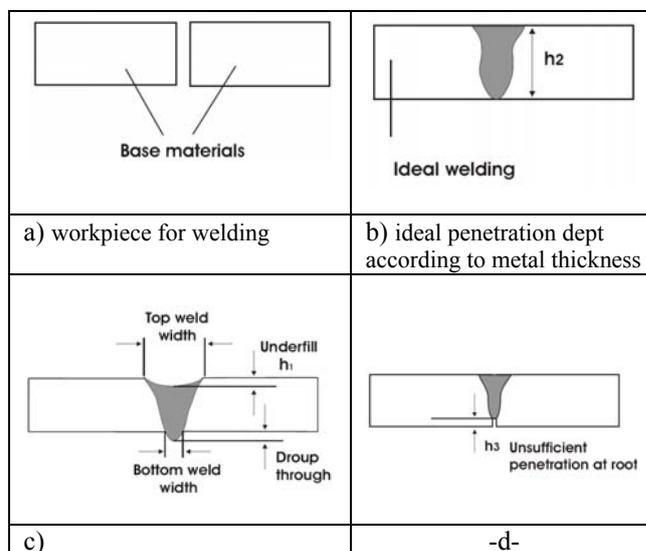
Figure 2 shows the Nd:YAG laser pulse waveform and pulse length measured in welding processes. The waveform of the pulse is modified using software. The peak power of 900 Watt for a 2.5 ms pulse length is used in the welding process. The average laser power is 360 W, the focal length is 200 mm, travel speed is 10 mm/s, repetition rate is 160 Hz and the pulse duration is 2.5 ms.



**Fig.2** The measured Nd:YAG laser pulse duration and waveform.

The unalloyed magnesium ingot (as-cast structure), produced by Dead Sea Magnesium, israel, and kindly supplied from TÜBİTAK-MAM at a thickness of 2.6 mm. The rectangular workpieces were cut into 15x40 mm pairs and specimens were positioned using a workpieces holder as illustrated in Figure 3-a without space between the workpieces. The butt welding of the workpieces welded in a specifically designed welding cabined, which is sealed and closed to achieve effective gas shielding and protect the extensional effects from the laboratory atmosphere. The laser focusing head has a synchronized camera system. The best position is found using the camera.

The geometry of the welded cross section gives very important information about the quality of the laser welding. Figure 3-b represents the ideal welding geometry. Figure 3-c and d represents the welding defects due to the uneffective welding parameters. The welded cross sections of the materials are characterized by using three geometric depths. The first depth is called “h<sub>1</sub>” depth and represents the dimensions of underfill defects. The second depth is called “h<sub>2</sub>” and represents the penetration depth of the welding. The third depth is called “h<sub>3</sub>” and represents insufficient penetration at the bottom of the weld. The h<sub>1</sub>, h<sub>2</sub> and h<sub>3</sub> depths are shown in figure 4 for workpiece 2.



**Fig.3** The butt welding principle of the materials.

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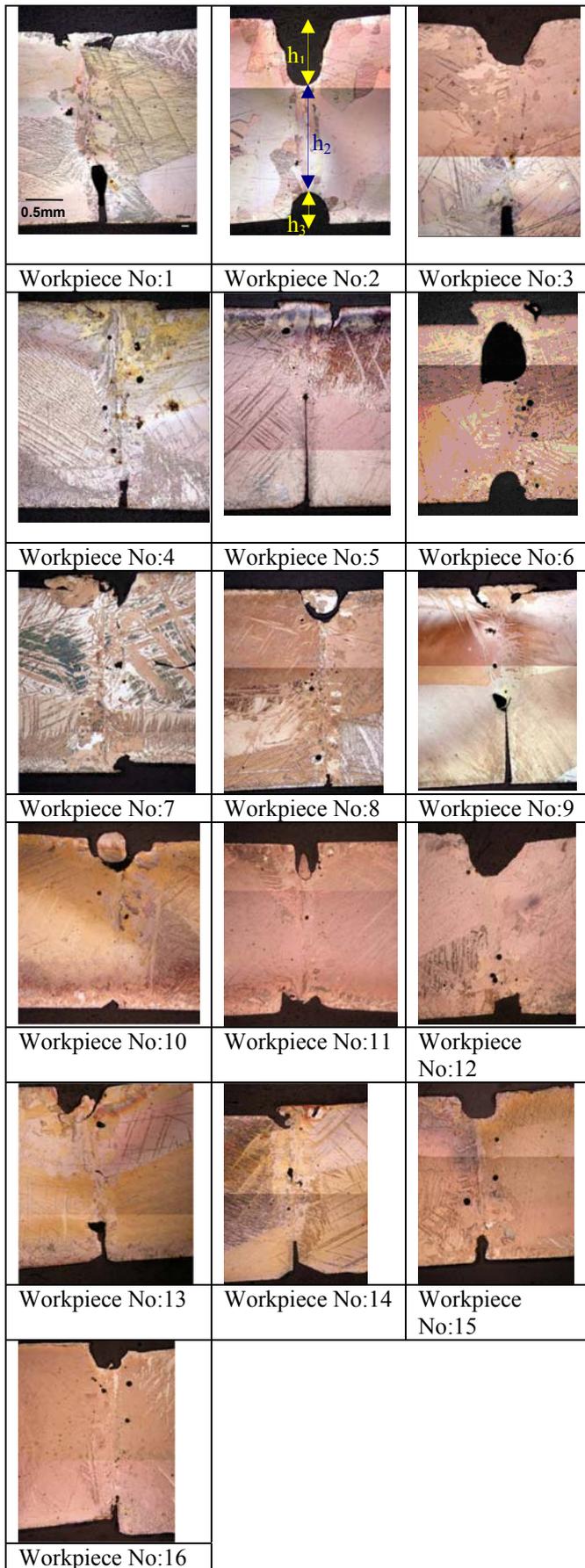


Fig.4 The micrographs of the laser welded cross-sections.

### 3. Results and Discussions

Figure 4 shows the optical micrographs of welded magnesium plates. The workpieces are welded changing the laser frequency, speed of welding, laser focus depths and gas pressures. The pulse duration is 2.5ms for all workpieces. The laser peak power is 900 W and gas pressure is 5 bar, the average power is kept constant 360 W for all workpieces, in table 1. Table 1 shows the effects of welding speed on penetration depth and weld width for Nd:YAG lasers. The penetration depth is decreasing approximately linear with increase in welding speed. Clearly the welding speed should be adjusted to provide the penetration depth required at a given power level.

Table 1. The effect of welding speed on laser welding

Workpiece No	Welding Speed (mm/s)	h <sub>1</sub> depth (mm)	h <sub>2</sub> depth (mm)	h <sub>3</sub> depth (mm)
2	2.6	0.80	1.35	0.4
3	5	0.46	1.67	0.44
<b>1</b>	<b>10</b>	<b>0.23</b>	<b>1.52</b>	<b>0.76</b>
4	20	-	2.21	0.36
5	40	-	1.09	1.46

As seen in Figure 4, the lowest welding speed of 2.6 mm/s results in high vaporization. The depth of underfill (h<sub>1</sub>) has the greatest value. The vaporization rate may be very high because of the high overlap ratio [4,5,7]. The melted area at the top of the workpieces is wider (top weld width) at low welding speeds. Low speed means that a high number of laser pulses transfer higher energy to unit area. This means that the top of the welding area stays in hot-melt state longer. Because of larger melt pool and longer beam/material interaction time, the hydrogen gas in the welding pool would have enough time to escape. This results in low porosity formation [1,5,7]. At higher welding speeds the depth of h<sub>1</sub> decreases. At workpiece 4 and 5 the depth of underfill (h<sub>1</sub>) are quite smaller compared to other sentence. On the other hand lower welding speed results in low porous material. A welding speed of 20 mm/s gives very porous cross section. There is low porosity formation occurred at higher welding speed. As expected the higher welding speeds with a lowest repetition rate result in lowest h<sub>2</sub> depth. This means limited energy transfer for unit area and the penetration depth is the smallest. Due to insufficiently melted region at the bottom of the workpiece at the highest welding speed gives the highest h<sub>3</sub> depth.

Table 2. The effect of laser frequency on welding

Work piece No	Peak Power (kW)	Pulse Frequency (Hz)	h <sub>1</sub> depth (mm)	h <sub>2</sub> depth (mm)	h <sub>3</sub> depth (mm)
6	3.6	40	0.87	1.3	0.44
7	1.8	80	0.27	2.28	0.1
8	1.2	120	0.47	2.5	0.1
<b>1</b>	<b>0.9</b>	<b>160</b>	<b>0.23</b>	<b>1.52</b>	<b>0.76</b>
9	0.72	200	0.21	1.16	1.20

The frequency of the laser pulses can be evaluated as the frequency of the energy transfer per unit area. Table 2 shows the effect of laser frequency when welding is done at the same welding speed of 10 mm/s. Average power is 360 W and gas pressure is 5 bar for all workpieces in table 2. Higher frequencies represent higher repetition rates (overload rates) and higher energy transfer per unit area. 120 Hz seems to show better results giving a deep penetration depth ( $h_2$ ). At higher frequencies it is observed that higher  $h_3$  depths are obtained. This means that at higher frequencies higher portion of the energy is absorbed at the top of the workpiece in order to melt the material. In addition, imperfect collapse of the keyhole and turbulent flow in the weld pool could also be linked with insufficient penetration depth [1,5,7].

At workpiece 9, the material was welded with the highest frequency. The porosity in the fusion zone increased with the increase in heat input. As seen in figure 4, there is a remarkable big porosity that occurred nearby the root of the welding. Also the higher heat input in cross section forced the material to heat deflection as a result of thermal expansion [1].

The instability of keyholes, however, was not the main cause for the formation of porosity during laser welding of magnesium. In addition, it was pointed out that turbulent flow of molten metal in weld pool can also form gas bubbles during laser welding of magnesium alloys [1,5,7]. Especially the higher the frequency the higher porosity formation has occurred.

Table 3. The effect of gas pressure on laser welding with 10 mm/s welding speed at 360 W average power and 900 W peak power.

Workpiece No	Gas pressure (bar)	$h_1$ depth (mm)	$h_2$ depth (mm)	$h_3$ depth (mm)
10	1	0.48	1.98	0.14
11	3	0.56	1.93	0.14
<b>1</b>	<b>5</b>	<b>0.23</b>	<b>1.52</b>	<b>0.76</b>
12	7	0.54	1.83	0.24
13	10	0.48	1.51	0.58

In literature there are very different results presented upon the shielding gas. The type and blowing properties of gas flow (the angle, position etc) have been reported as an important parameter [1,7]. In our study we blow the shielding gas approximately from 15.5 cm above the surface at normal angle to the material. When the results are investigated it is pointed out that the gas pressure is one of the important welding parameters in laser welding of magnesium. Compared the other metallic materials magnesium has a quite low melting point. Also the thermal conductivity and heat transfer coefficient influence the results. But the low melting point is considered to be (more predominantly) responsible for this result. Because of this material property the temperature of melted welding pool is not so high and this results in trend of cool in shorter times. The shielding gas temperature (argon) has a room temperature. Since the melted material temperature higher than room temperature,

gas flow cools the welding area. When Table 3 is investigated, it is seen that the penetration depth of welding ( $h_2$ ) is decreasing by increasing gas flow rate. On the other hand it is found that the porosity dimensions increase at higher gas flow rates. This is another evidence of rapid cooling. The reaction gases couldn't find sufficient time and low enough viscosity due to the cooling effects of shielding gas.

Shielding gas flow direction was found to have a significant effect on the weld geometry. If the gas flow was too weak, there would be insufficient weld protection, while too strong gas flow would disturb the weld geometry, or cause defects. When the gas from the feed tube above the weld was not aligned with the traverse direction, a side cut would occur. Besides, if it was in the opposite direction, an irregular weld bead would occur [1,5]. In our study we investigated that remarkable underfill defects and sideblow defects (especially at the pressures higher than 5 bar) are encountered as a result of higher gas flow.

Table 4. The effect of laser defocused distance on laser welding

Workpiece No	Defocused distance (mm)	Average Power (W)	$h_1$ depth (mm)	$h_2$ depth (mm)	$h_3$ depth (mm)
14	-1.95	360	0.33	1.73	0.51
<b>1</b>	<b>-1.3</b>	<b>360</b>	<b>0.23</b>	<b>1.52</b>	<b>0.76</b>
15	-0.65	360	0.36	1.84	0.39
16	0	360	0.20	1.94	0.45

The position of focal point has an important influence on welding process and quality. The focal plane should be set where the maximum penetration depth or best process tolerances are produced.

The results showed that an adequate weld could be obtained for a focal position on the surface of the workpiece as also suggested and reported in other studies in literature [1]. As represented in table 4 the penetration depth ( $h_2$ ) is increasing as the laser focus point gets closer to the material surface.

In literature for thin plates (2.5 and 3 mm), the best welds according to penetration depth, aspect ratio and sag were reported to be achieved when the focal point was adjusted on the surface of the workpiece, whereas for thick plates (5 and 8 mm) a position of 2mm below the surface of workpiece proved to be the best [1,5]. Thus, the focal position should be moved deeper into the material for thicker workpieces.

One of the major concerns during the welding of magnesium and aluminum alloys is the presence of porosity in the weld metal that can deteriorate mechanical properties, particularly tensile strength and elongation. The dimensions of the porosities and their distributions in cross-sections and the arial portion in cross section in welding have an important role. As discussed above, the porosity in the fusion zone increased with the increase in heat input, *i.e.*, increase in the laser power and decrease in the welding speed. Pore formation has been attributed to hydrogen rejection from

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the solid phase during solidification and imperfect collapse of the keyhole. In addition, turbulent flow in the weld pool has also been linked with porosity formation [1,5]. Table 5 shows the porosity diameters for the workpieces provided in Figure 4.

Table 5. The diameter of biggest porosity in cross section

Workpiece No	Diameter of porosity ( $\mu\text{m}$ )		Diameter of porosity ( $\mu\text{m}$ )		Diameter of porosity ( $\mu\text{m}$ )
1	78	7	94	12	82
2	30	8	64	13	88
3	19	9	147	14	88
4	85	10	25	15	104
5	100	11	56	16	79
6	94				

When the laser energy input was more than the required level for a full penetration, large holes or weld dropout would occur [1,5,7]. No weld drop type defect was observed in our study. Opposite to weld drop, we observed gaps at the root of the welding as a result of insufficient melting. This is due to the short interaction time or the lower power density, while the high viscosity liquid is not able to fill the root of the welding area. This defect would significantly reduce the load capability of the weld. This problem could be overcome by selecting the appropriate welding speed and the optimum welding energy.

The gas porosity may originate mainly from initial pre-existing pores, from the interaction of molten magnesium with surrounding air, or with moisture in entrapped surface oxide films. It is speculated that hydrogen mainly results from the interaction of water vapor ( $\text{H}_2\text{O}$ ) with magnesium. Hydrogen porosity greatly depends on the surface preparation of parent material [1,5,7].

The formation of gas porosity is greatly influenced by weld processing parameters. Pore area fractions go through a maximum with welding speed. The time for the formation of gas porosity decreases with increasing cooling rate in the weld pool (increasing welding speed). At slow welding speeds, the interaction time (beam diameter/welding speed) is long enough for gas porosity to nucleate in large quantity, grow and escape from the molten pool, mostly as a result of buoyancy or other convective flow processes. At high welding speeds, as is usually experienced in laser welding, gas pores will have insufficient time to nucleate and grow. If gas remains trapped in a supersaturated matrix condition, relatively pore-free welds can be obtained. Thus, the porosity volume fraction in the fusion zone usually decreases with welding speed [1,5,7].

The net increase in pore volume from the expansion of initial pores also decreases with decreasing power. The density of pores increases with increasing welding speed and decreasing laser power due to reduced time for pores to coalesce. The amount of porosity does not change consistently with beam defocusing [1,5,7].

In summary, the technical options to minimize gas pores would include use of base metal with low pore density, removal of hydrogen sources before and during welding, and production of a hydrogen-oversaturated weld fusion zone by rapid solidification. Prior to welding, the oxide and contaminated surface layers should be removed from the workpiece and filler metal, and high-grade (low-dew-point) shielding gases should be used. Low laser power, high welding speed and small beam diameters may increase solidification rate and lead to suppression of nucleation and growth of gas pores [1,5,7].

Previous studies have shown that some Mg is lost from the weld metal during laser welding of Al–Mg alloys as a result of preferential vaporization of the high vapor pressure of Mg. With an expected loss of Mg and therefore reduced solid solution strengthening, hardness profiles would be expected to show a corresponding drop in hardness in the weld metal. This decrease in hardness in the weld metal is owing to preferential loss of Mg during welding [1,5,7,8]. Micro-hardness measurements were done in two directions. The first direction is from point A to point B nearby the surface of the materials, as shown in Fig. 5. The secondary direction is from point C to D just above the root of the welding. Measured Vickers microhardness profiles through representative welds made in workpiece 14 are shown in Fig. 6. The hardness measurements were done at the surface and then just above the root of the weld. In our cases, the hardness profile showed a slight decrease in hardness from the base metal value. Through the heat affected zone (HAZ) the peak in hardness occurred just inside the fusion boundary. The peak in hardness values were approximately 5 HV above that of the base metal. There was a decrease in hardness compared to the approximate values of the base metal towards the outer area of the weld. The micro hardness measurements were done at whole workpieces and approximately similar results are measured. This is why only the hardness distribution of workpiece 14 is illustrated in Figure 6 as a representative of other welded workpieces.

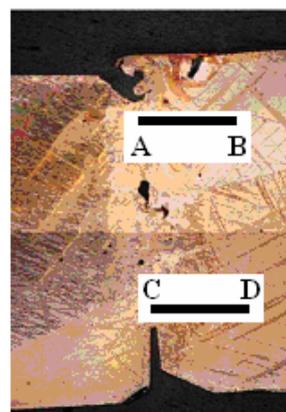


Fig.5 The microhardness measurement paths.

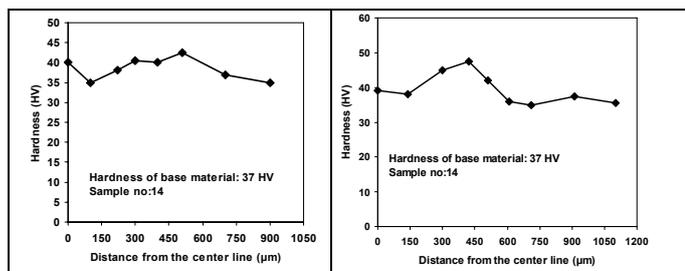


Fig.6 Measured vickers microhardness profiles for sample 14.

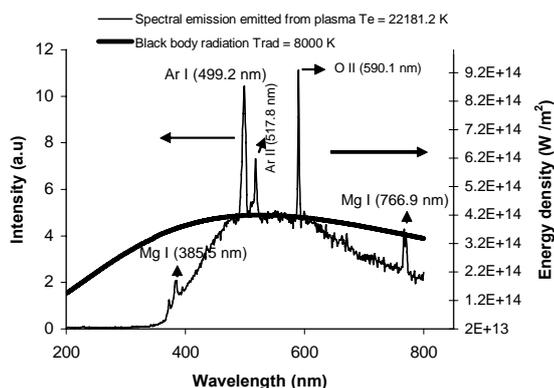


Fig.7 The magnesium and argon spectrum.

Welding process can be monitored online using spectroscopic methods. Using spectral lines ratio, temperature of the laser plume can be deduced. Hence, required laser input energy to melt the material can be obtained. Figure 7 shows the obtained spectrum of magnesium and shielding Argon gas for the experimental condition: average laser power is 360 W, focal length is 200 mm, travel speed is 10 mm/s, repetition rate is 160 Hz and the pulse duration is 2.5 ms. The spectrum is recorded during the laser welding of magnesium using a Newport OSM-100 Spectrometer (spectrometer range: 200nm-1100nm). The spectral lines belong to Ar and Mg is observed [8]. The continuum emission is fitted with black body emission curve.

Power absorbed from the incident laser beam is converted to electronic excitation and therefore can be radiated at a variety of wavelengths. In the calculation the electron temperatures of plasma plume were determined from the relative intensities of the 4991.33 Å Ar I and 5178 Å Ar II lines using

$$T_e (^{\circ}K) = \frac{5040(E_s - E_p)}{\log \left[ \frac{g_s A_{sq}}{g_p A_{pq}} \right] - \log \left[ \frac{\lambda_s}{\lambda_p} \right] - \log \left[ \frac{I_{sq}}{I_{pq}} \right]}$$

where  $E_s$  and  $E_p$  show the energy of the p state and q state in eV,  $g_s$  and  $g_p$  are the degeneracy of the excited levels,  $\lambda_p$  and  $\lambda_s$  are wavelengths of spectral emission,  $I_{sq}$  and  $I_{sp}$  are the spectral intensity for a transition between excited levels and ground states [9]. The blackbody temperature is obtained as  $\approx 8000K$  and electron temperature is deduced as

2 eV using emission from Argon shielding gas line ratios. The laser plume is assumed to be in thermal equilibrium.

#### 4. Conclusion

The Nd:YAG laser welding parameters of magnesium are optimized in order to get crack-free laser welded joints, with low porosity and good surface quality. The 900 Watt peak power is enough to weld magnesium plates with 2.5 ms pulse duration. The optimized laser welding parameters are systematically changed and the welded cross section of the material is investigated by changing the laser power, pulse length and welding speed and shielding gas pressure. During the welding studies the laser beam profile, pulse frequency, pulse profile etc. are measured in order to be sure of the realized working parameters. The welding geometries and defects are observed with micrographs and micro hardness measurements.

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